SOME OBSERVATIONS ON THE STRUCTURE OF SHALLOW TYPHOONS

George Varga

United States Naval Postgraduate School

THESIS

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OF SHALLOW TYPHOONS

by

George Varga

Thesis Advisor: R. L. Elsberry

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Some Observations on the Structure of Shallow Typhoons

by

George Varga
Lieutenant Commander, United States Navy
B.S., United States Merchant Marine Academy, 1961

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ABSTRACT

During the past few years the existence of tropical cyclones of typhoon intensity, but lacking the vertical extent of the "classical" model, have been reported. Five such "shallow" systems were investigated by compositing reconnaissance and rawinsonde data with respect to the center. Although emphasis was placed on POLLY (1968), a composite model was derived from the five storms. Some of the characteristics found in the model were the lack of convective activity, the existence of a warm core in the lower levels but very little warming aloft, and an open eyewall rather than the closed eye found in classical typhoons.

Some comparisons with the classical model are made but detailed reconnaissance data are needed to explain the differences between shallow and normal typhoons.

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I. INTRODUCTION

The development, maintenance and structure of tropical storms and typhoons has been well described by Riehl (1954). With the advent of hurricane/typhoon reconnaissance and the availability of upper level data the typhoon model was further refined by Riehl (1963), La Seur (1966), and Gray (1968). Fett (1966) formulated the depiction of tropical cyclone development into various diagramatic stages on the basis of nearly simultaneous satellite photographs and maximum observed wind speed. In this scheme a tropical depression which had cloud patterns typical of Stage C normally had maximum winds of 30 knots. It was found, however, that reconnaissance flights into some depressions which appeared to be Stage C found winds of tropical storm intensity or greater near the surface.

Fett (1968) cited typhoon BILLIE (1967) as a good example of such a phenomena. Among the primary characteristics of BILLIE was the lack of a wall cloud around the eye and the absence of major convective activity and vertical development. Fett indicated cloud tops 4000 to 5000 feet near the eye of BILLIE, whereas the vertical development of "normal" typhoons can be expected to reach elevations around 50,000 feet according to La Seur (1966) and Riehl (1963). Because typhoons of the BILLIE variety lack vertical development, they have been referred to as "shallow typhoons" in this report.

The Naval Weather Research Facility's contribution to Project STORMFURY (1968) indicated that typhoon/hurricane reconnaissance crews have reported hurricane-intensity tropical cyclones with cloudiness below the 700 mb level near the eye and the lack of a definable eye wall. In correspondence with Elsberry, Kerr[1] described a possible shallow hurricane that existed in the early 1950's as:

> "...The eye was the usual 15-20 miles in diameter and everything seemed to be rather normal as far as observations were concerned. However, when we started circling in the eye and climbing to higher altitudes for additional data (flight level at this time 500 - 800 feet) we noted that we could see plenty of blue sky and we broke out on top of everything at something like 5-7000 feet. The whole hurricane appeared as a doughnut below us and we had good visibility in all directions with no high clouds observable."

Sadler (1967) in his discussion of the Tropical Upper Tropospheric Trough (TUTT) as a secondary source of typhoons, reported the development of typhoon KATHY in August 1964. The 0335 GMT 15 August reconnaissance report of KATHY indicated a circular eye 50 miles in diameter, open in the north semicircle, with maximum cloud tops at 17,000 feet. Sadler's upper level streamline analysis of typhoon KATHY at 0000 GMT on the 15th depicted northeasterly flow above the vortex rather than cyclonic outflow as expected with a normal typhoon. These characteristics suggested the existence of a typhoon that lacked the vertical development normally expected, hence possibly another shallow typhoon.

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[1] Personal correspondence from J. L. Kerr, formerly with the U.S. Navy Airborne Early Warning Squadron 4, to Professor R. L. Elsberry, Department of Meteorology and Oceanography, Naval Postgraduate School, January 24, 1970.

The purpose of this paper is to attempt to delineate the structure of these typhoons and to discuss possible mechanisms of maintenance. In addition to typhoon BILLIE, which Fett (1968) described in detail, tropical storms POLLY (1968), OLIVE (1968), NADINE (1968) and LORNA (1969) were chosen for investigation. The latter four systems were picked on the basis of correspondence with the U.S. Navy Airborne Early Warning Squadron One (VW-1) based at Guam, Mariana Islands. It was felt that these four best fitted the characteristics of typhoon BILLIE as discussed by Fett (1968) and would yield some data for describing the structure of these systems.

The main concentration of effort was on POLLY because of the best combination of land and reconnaissance reports. Typhoon BILLIE received less emphasis while NADINE, OLIVE, and LORNA were examined superficially and need to be investigated further.

II. DATA SOURCES AND COMPOSITING

Typhoon reconnaissance reports (RECCO) and rawinsonde reports for the storms were obtained from the National Meteorological Data Center, Asheville, N.C. and the U.S. Fleet Weather Central/Joint Typhoon Warning Center (JTWC), Guam, Mariana Islands.

The data were composited with respect to the storm center and the direction of motion for time spans ranging from 36 hours to four and a half days. The time span was determined by the constancy of the individual typhoon track and by the intensity of the system. With compositing there is the danger of glossing over possible anomalies which could be important in an investigation such as this. However, it was felt that only by compositing could enough data be gathered to make an analysis of the typhoon possible. The reconnaissance reports alone were not sufficient to describe the typhoon structure during a single synoptic time period. The plots of POLLY and BILLIE also included surface ship data.

With the exception of aircraft data, each report was plotted relative to the "best-track" center positions of the system given in the Annual Typhoon Report of the JTWC. The aircraft reports were plotted relative to the typhoon eye positions reported by that aircraft. This careful positioning of the RECCO reports was especially important in the regions of strong gradients near the center.

Wind reports were plotted with respect to true north and transformed to the coordinate system relative to the center of the typhoon. The course and speed of the system was vectorially

subtracted from the reported wind direction and speed. The average speed of the typhoon was computed over twelve hours before and after the time in question. Therefore the wind force and streamline analysis were based on relative winds so that the maximum winds to the right of the direction of motion were somewhat reduced.

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III. TRACKS AND CLIMATOLOGY

Figures 1-4 depict the tracks of the five systems considered. The dotted portion of the track indicates the formative stages, the solid indicates the tropical storm and typhoon stage. The stippled portion of each figure indicates the extreme typhoon and tropical storm track limit for the period, based upon climatology obtained from U.S. Pacific Fleet, Commander Cruiser-Destroyer Force (1964).

Typhoon BILLIE (Fig.1), tropical storms POLLY (Fig.3) and LORNA (Fig.4) formed in regions favorable for development. However, POLLY deviated from the normal track, and reached tropical storm intensity at about 21 N. POLLY did not follow the normal track until recurvature to a northeasterly course in the East China Sea. OLIVE and NADINE (Fig.2) also developed in regions favorable for tropical storms, but further north than the others.

On the basis of comparison of actual tracks and climatology, it did not appear as though the shallow systems deviated significantly from the preferred development regions or from the climatological tracks. However, the tracks were generally complex with loops or southwesterly movements. OLIVE moved from west to east along the track shown, apparently as a "Fujiwhara effect" with respect to NADINE. POLLY was the only one of the five to deviate much from the expected track. Because most of POLLY's track as a tropical storm was north of 25 N, POLLY may have intensified from a system in the Tropical Upper Tropospheric Trough (TUTT) as discussed by Sadler (1967). However, comparison of the

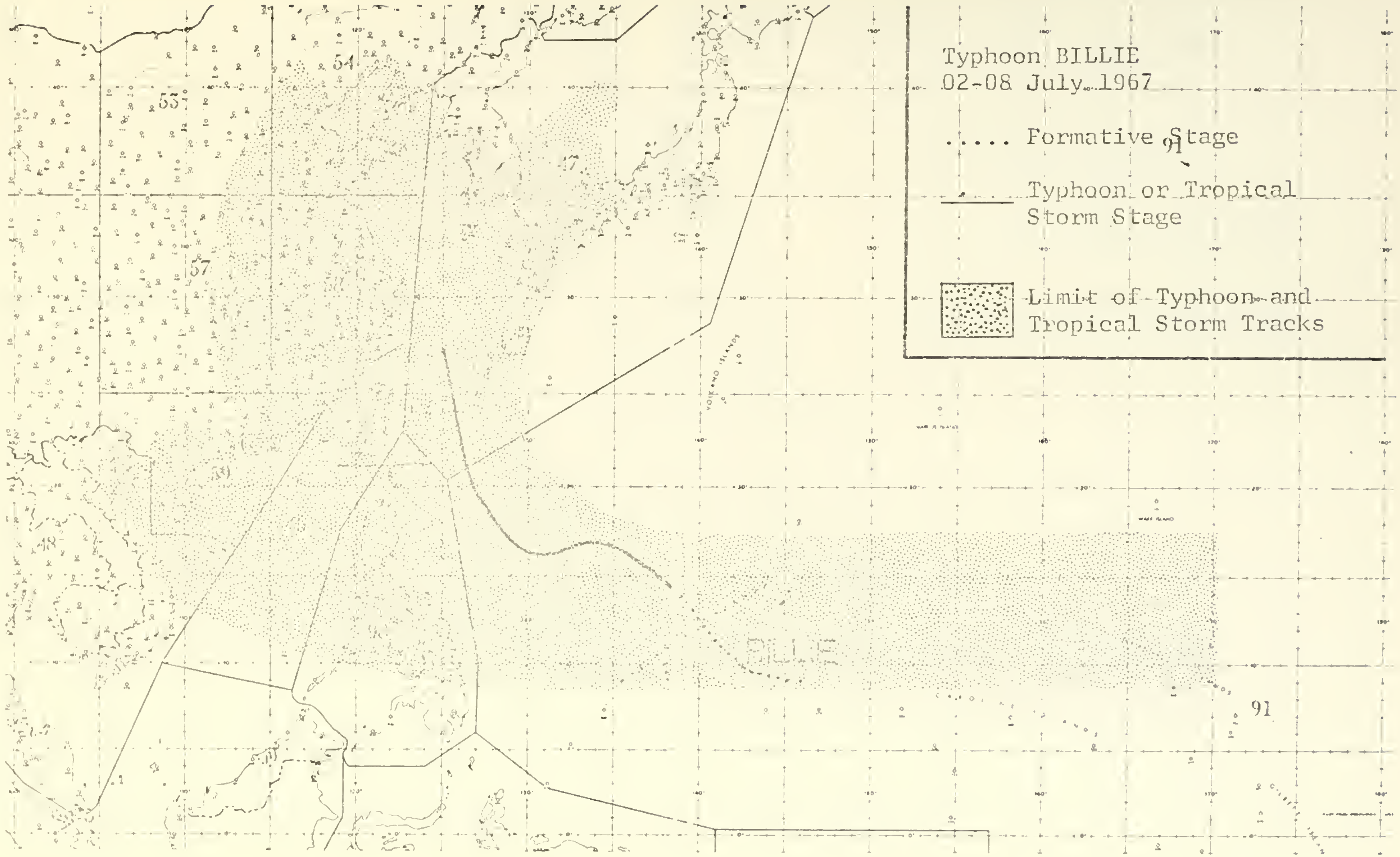

Fig. 1. Track of Typhoon BILLIE, July 1967, and the climatology of typhoon and tropical storm track limits for 1-10 July.

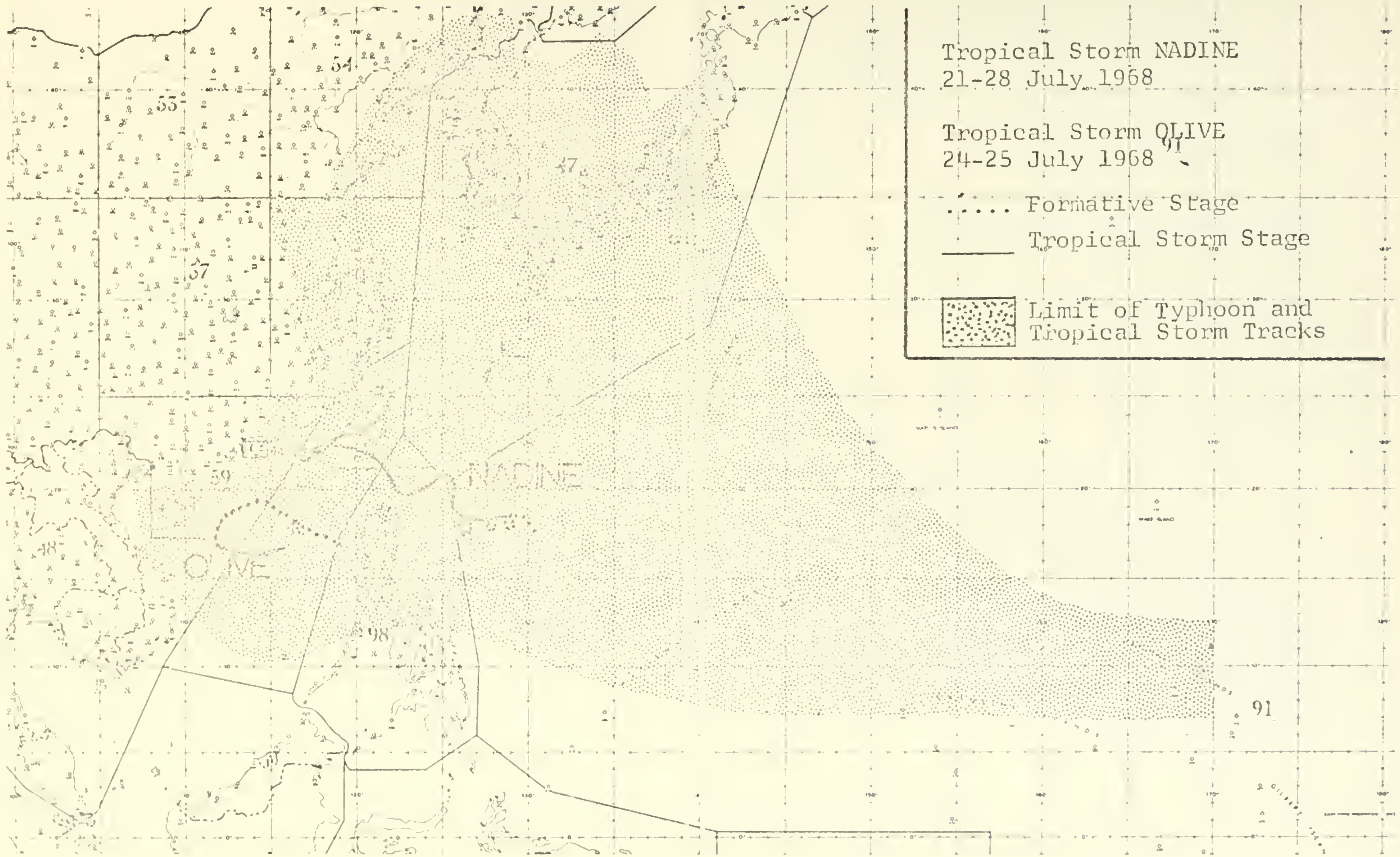

Fig. 2. Tracks of Tropical Storms NADINE and OLIVE, July 1968, and the climatology of typhoon and tropical storm track limits for 21-31 July.

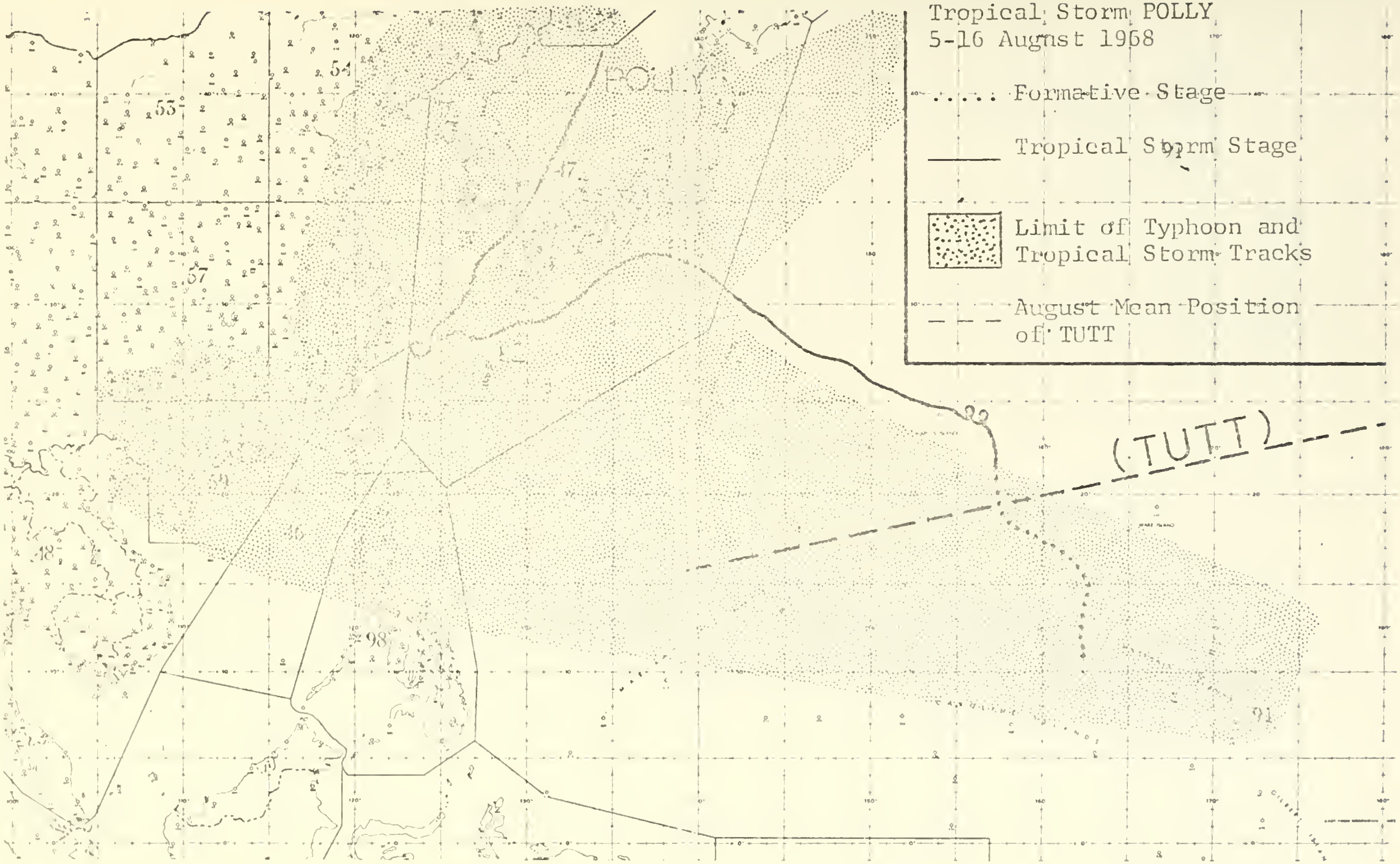

Fig. 3. Track of Tropical Storm POLLY, August 1968, the climatology of typhoon and tropical storm track limits for 1-20 August, and the mean position of the Tropical Upper Tropospheric Trough (TUTT) for August according to Sadler (1967).

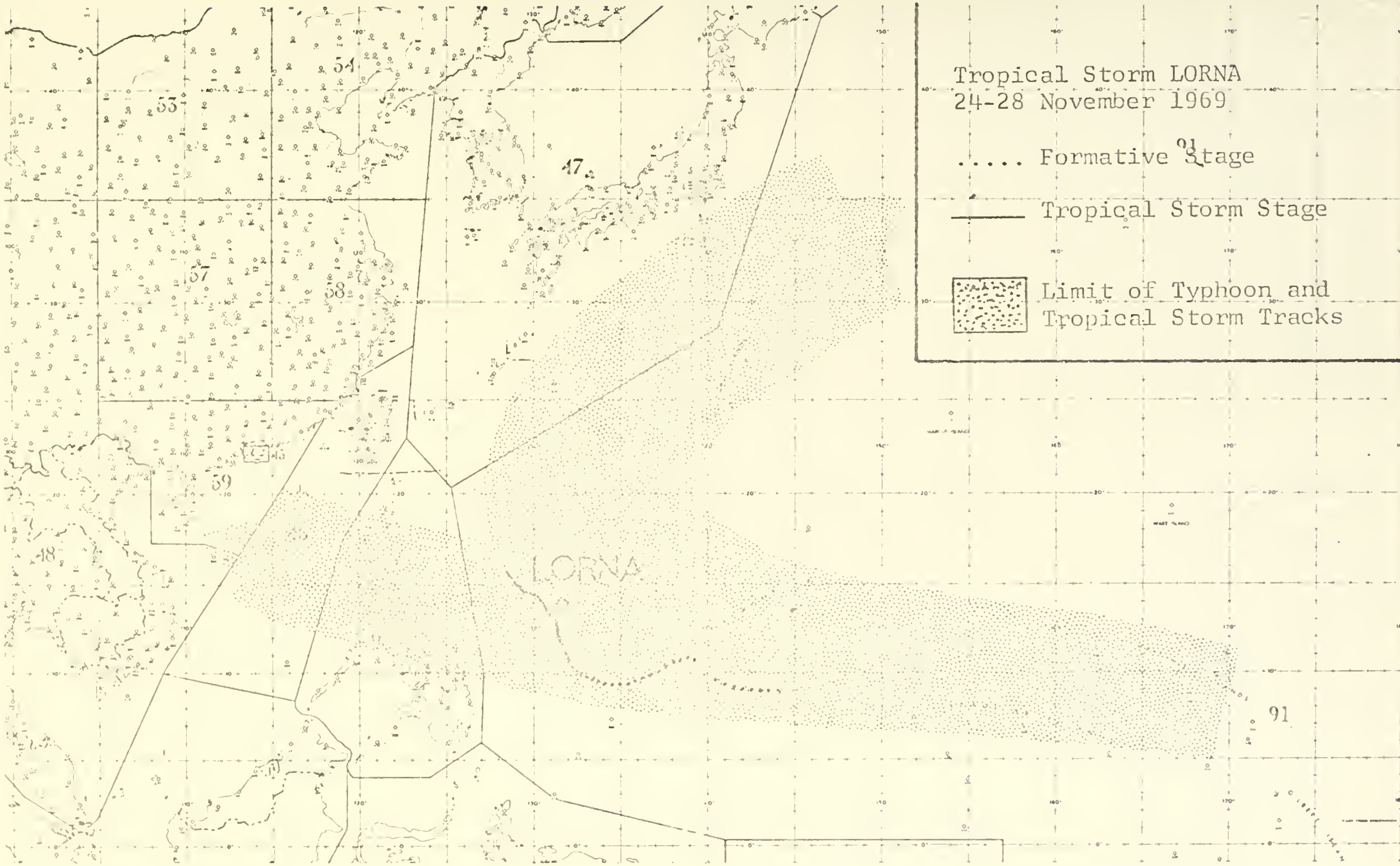

Fig. 4. Track of Tropical Storm LORNA, November 1969, and the climatology of typhoon and tropical storm track limits for 16-30 November.

climatological position of the TUTT for the month of August (Fig.3) and the area of formation of POLLY indicated that POLLY probably did not originate in the TUTT. It may have been that the TUTT extended considerable further south during the early period, August 5-6, of POLLY but this was not investigated for this report.

IV. ANALYSIS OF POLLY

POLLY was selected for intensive study because of good coverage of rawinsonde and aircraft reconnaissance data. The composite analysis of POLLY covered the period from 0000 GMT 10 August to 1200 GMT 14 August 1968.

A. HEIGHT FIELDS

The analyzed height fields of tropical storm POLLY for the 1000, 700, 500 and 200 mb levels are depicted in Figs. 5-8. The 1000 mb height field was augmented by conversion of marine surface pressure reports to 1000 mb heights by using 1 mb = 8.7 meters. Pressure heights at the center during the period 0000 GMT 10 August to 1200 GMT 14 August are indicated in Table 1.

TABLE 1

Pressure heights used in the composite analysis of POLLY.

Level (mb)	Height (m)
1000	-244
700	2841
500	5750
200	12435

Central pressures at the lower two levels were typical values based on many reconnaissance eye reports. During the period the lowest surface pressure report was 968 mb at 0300 GMT 14 August with a corresponding 700 mb height of 2832 meters. The central value at 500 mb was based upon the only eye penetration available

at that level. For the 200 mb level there were no reconnaissance reports available. Consequently the central value was based upon thickness and vertical consistency considerations.

At 200 mb it was very difficult to analyze the heights and to fit them with the temperature and wind fields. For consistency with the better defined streamlines a considerable number of heights appeared to be in error by as much as ±70 meters.

B. TEMPERATURE

Temperature fields for POLLY were constructed using radiosonde and rawinsonde checked data, surface ship and aircraft flight reports. The 1000 mb field was constructed by the extrapolation of the temperatures from ship and low level flight reports. Temperature reports at 700 mb were augmented by the extrapolation of RECCO reports near the 700 mb level. A standard tropical lapse rate from Riehl (1954) was used for extrapolation. Analyses near the typhoon center at 1000 mb and 700 mb were primarily based on aircraft reports. At the 500 mb level the only eye penetration report available indicated an increase from -1.0C outside the eye to +1.0C inside. No 200 mb flight reports were available

Figs. 5-8 depict the temperature fields for the 1000, 700, 500, and 200 mb levels. Analysis at 1000 mb indicated a slight cooling trend towards the center from 27C within about 60 n mi of the center to less than 26C over the eye. This cooling is consistent with the classical model of a typhoon. However, the low-level eye penetrations listed in Table 2 indicate an increase in temperature in the immediate region of the eye. After reduction

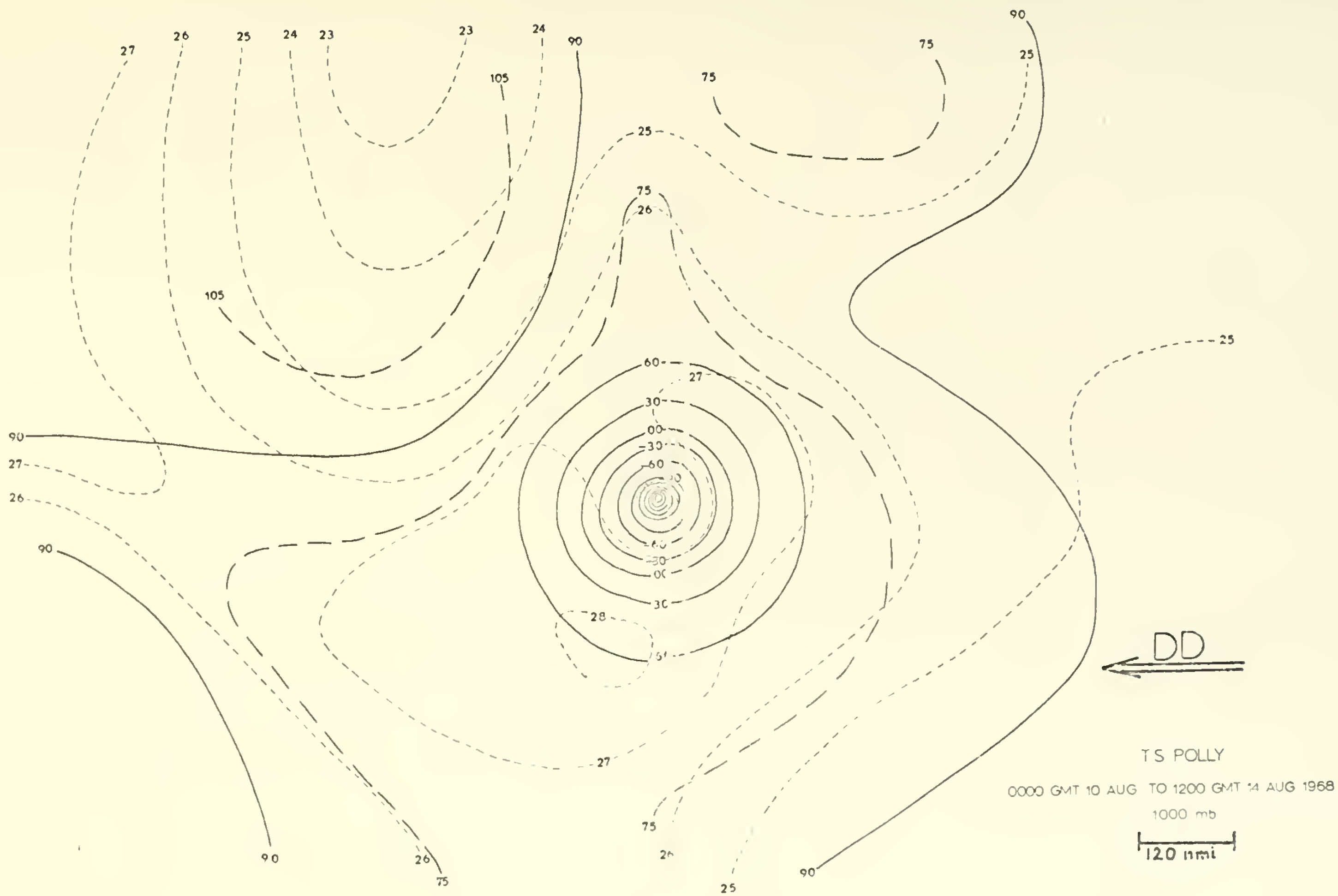

Fig. 5. The 1000 mb height and temperature fields for tropical storm POLLY. Arrow indicates the direction of movement.

Fig. 6. The 700 mb height and temperature fields for tropical storm POLLY. Arrow indicates the direction of movement.

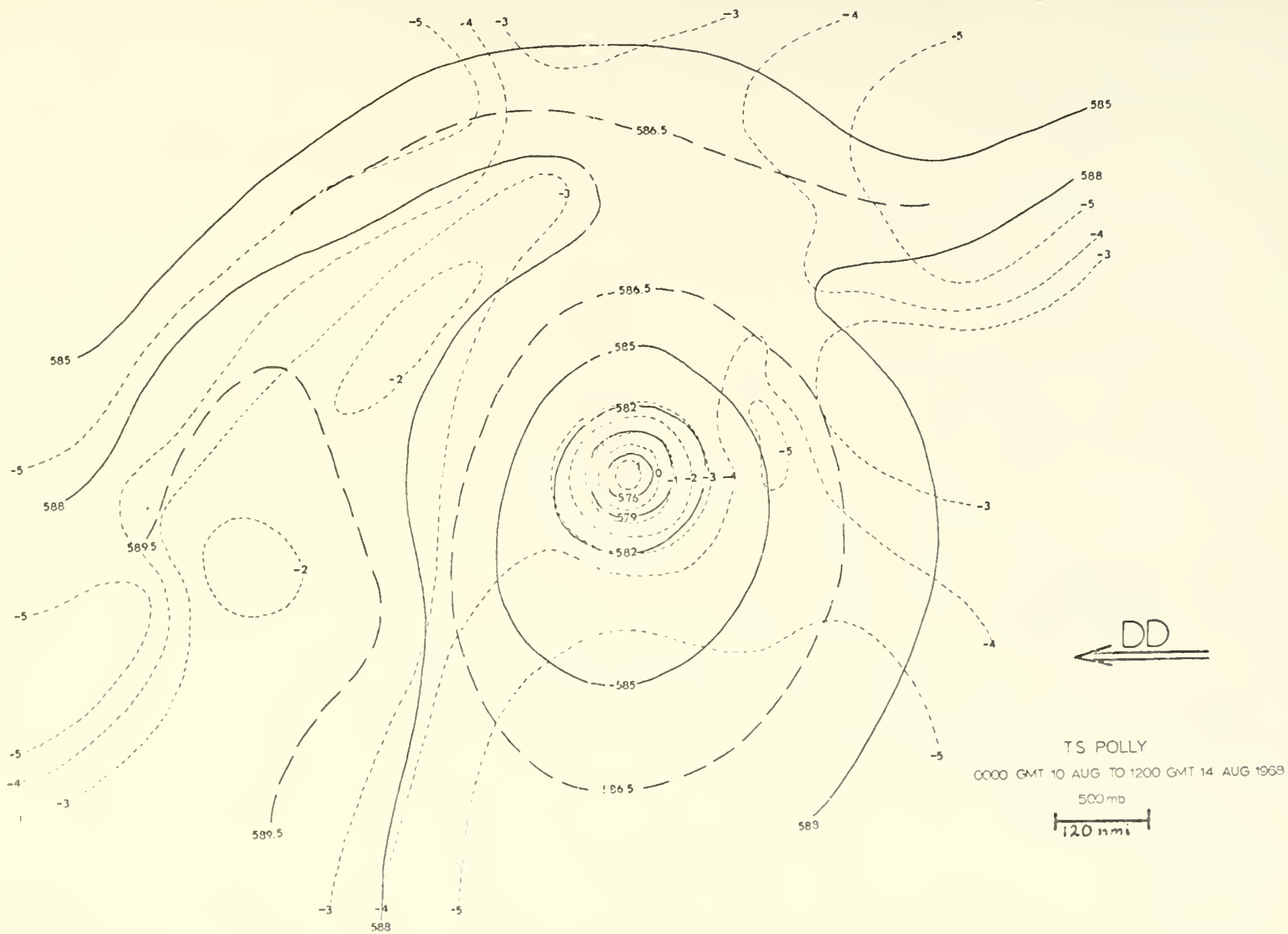

Fig. 7. The 500 mb height and temperature fields for tropical storm POLLY. Arrow indicates the direction of movement.

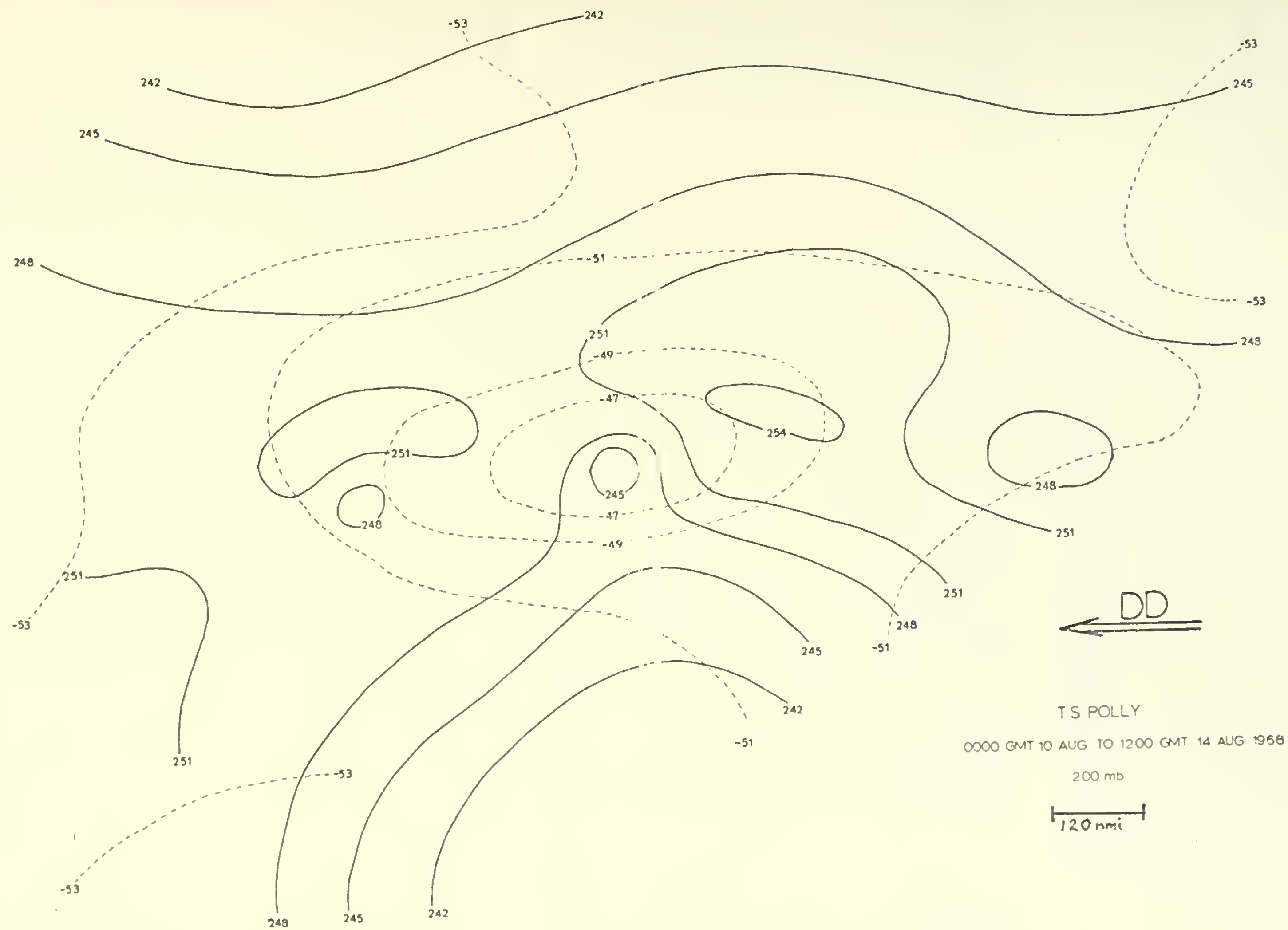

Fig. 8. The 200 mb height and temperature fields for tropical storm POLLY. Arrow indicates the direction of movement.

of these temperatures to 950 mb the average maximum eye temperature was 26.6C with an average increase of 1.5C. According to La Seur (1966) a 2C increase can be expected at 950 mb in a mature hurricane.

TABLE 2

Low-level eye penetration temperature reports for tropical storm POLLY, August 10-15, 1968.

Date/Time (GMT)	Max T in eye (°C)	Flight Level (mb)	Temp. outside eye (°C)	Flight Level (mb)	Temp. Increase (°C)
10/0915	25.8	947	23.3	950	2.5
12/0955	27.9	956	26.3	960	1.6
13/1050	28.0	963	26.0	956	2.0
14/0925	24.5	968	24.0	969	0.5
15/0900	25.0	956	24.0	950	1.0

At 700 mb on the composite analysis (Fig.6) the maximum temperature within the eye is about 16.5C. The highest 700 mb eye temperature indicated by RECCO reports (Table 3) was 18.5C. The entire 700 mb field was 2 to 4C warmer than the mean tropical atmosphere. Within 90 n mi of the center the deviation was even greater. Eye penetration reports for 700 mb (Table 3) indicated a definite temperature increase near the eye. The largest temperature increase occurred during the 0300 GMT 14 August penetration. However, at this time the eye wall was described in the RECCO report as being closed with moderate feeder bands in all quadrants. Average maximum temperature was 15.7C with an average increase of 4.2C, including the 14/0300 GMT report. La Seur's (1966) model indicated an increase of 5 to 6C at 700 mb. It should be noted

that about half of the reports in Table 3 indicate an outside eye temperature lower than those appearing some distance from the center in Fig. 6. Thus, upon approaching the center of the storm one would expect the temperature to decrease slightly and then rise rapidly near the eye. Compositing the data tends to obscure this particular feature.

TABLE 3

Eye penetration temperature reports at 700 mb, unless indicated, for tropical storm POLLY, August 10-15, 1968.

Date/Time (GMT)	Max Temp in eye (°C)	Temp out side eye (°C)	Temp Increase (°C)
10/0240	14.5	9.5	5.0
11/0300	14.0	11.0	3.0
11/1558	16.6	9.1	7.5
11/2115	17.0	14.0	3.0
12/0300	14.0	10.0	4.0
13/0000	16.5	13.0	3.5
13/0225	16.5	13.0	3.5
13/1430	15.6 (at 695mb)	13.8 (at 695mb)	1.8
13/2100	14.5	11.0	3.5
14/0300	18.5	10.5	8.0
14/2120	17.0	12.0	5.0
15/0250	14.0	12.0	2.0

A 2C warming near the eye at 500 mb contrasts with La Seur's (1966) typhoon model which had a 7-8C warming at this level. On the basis of available data, the amount of warming

within the eye at 500 mb was considerably less than might be expected. However, the entire 500 mb field was 1 to 6C warmer than the mean tropical atmosphere.

Rawinsonde data at 200 mb indicated a temperature increase from -49C to about -45C with elliptical rather than circular isotherms. Furthermore, the analysis indicated considerable warm advection from the region near the center. In a fully developed typhoon approximately 10C warming can be expected at this level according to La Seur (1966). As in the case of the lower levels, the 200 mb temperature field was warmer than the mean tropical atmosphere by 2C to 5C away from the center

Fig. 9 depicts the 1000-700 mb, 1000-500 mb, 700-500 mb and 500-200 mb thicknesses on a cross section along the direction of motion of POLLY. An increase of about 160 m within a 60 n mi radius of the center was observed in the 1000-500 and 700-500 mb thickness patterns. The striking feature was the 500-200 mb thickness plot which showed very little warming in that layer. Over a distance of 120 n mi on either side of the center the thickness pattern increased by only 30 m. Lack of variation in this layer suggested a near barotropic atmosphere where the geostrophic vertical shear is zero. However, examination of Fig. 16 shows that the actual 500-200 mb wind shear was large. In a later section the actual wind shears are compared with those calculated from these thicknesses or mean temperatures.

The general warming in the lower troposphere indicated by the larger eye temperature increases and corresponding thickness patterns (Fig.9) may have been the result of subsidence. With the absence of deep convective clouds, it would appear that

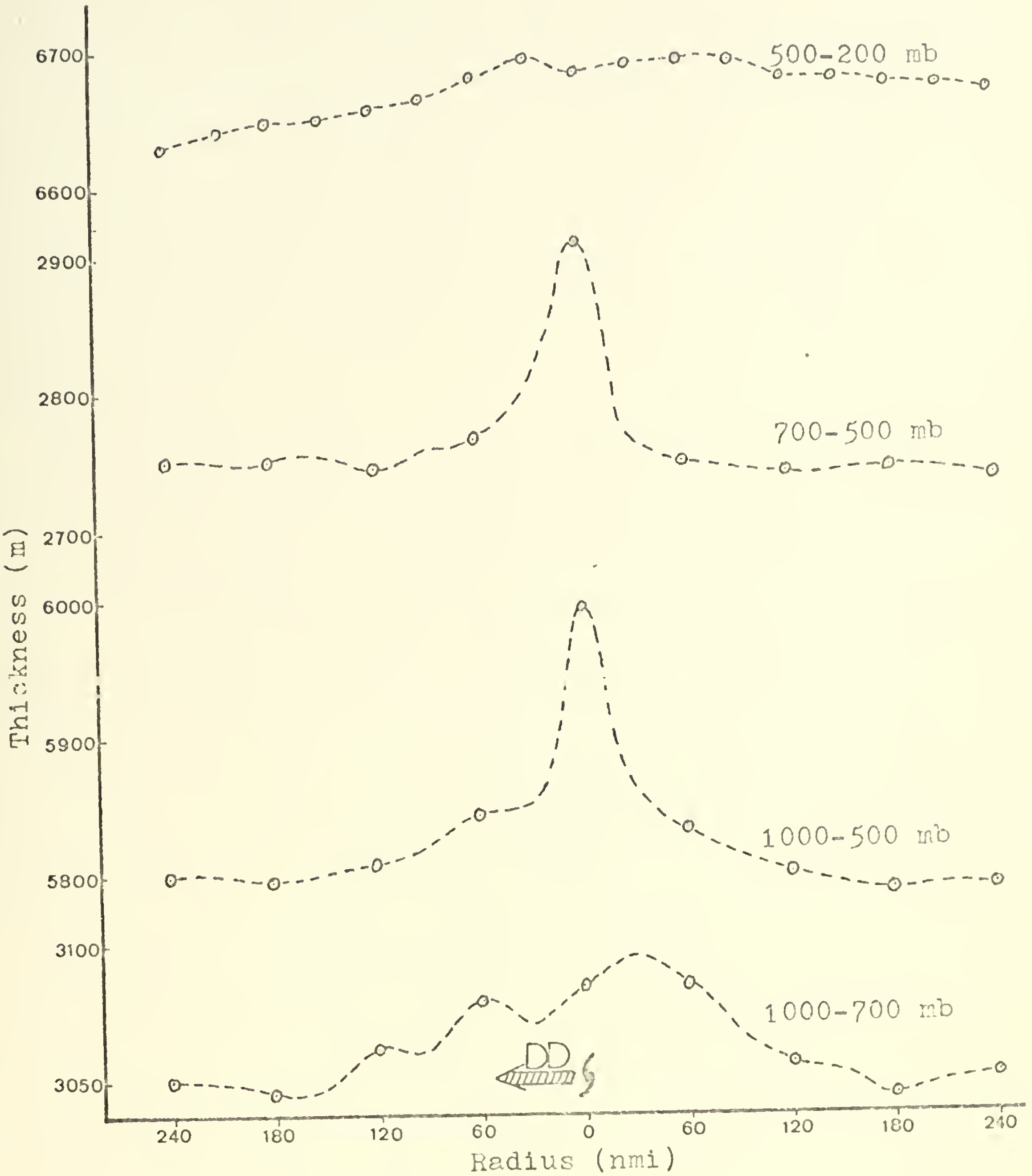

Fig. 9. The 1000-700 mb, 1000-500 mb, 700-500 mb and 500-200 mb thickness profile along a cross section in the direction of movement of tropical storm POLLY, August 10-14, 1968.

release of latent heat was not an important factor as is the case for normal typhoons.

The shallow typhoon appears to have the temperature structure of a mature typhoon only at the lower levels. A very large warming associated with upper level heating in mature typhoons is absent. In this sense shallow typhoons seem to be marginal tropical circulations in which a warm core is developed at low levels but the absence of deep convection prevents full development.

Cause of this low level warm core development was not investigated, however, possible mechanisms are suggested. Radiational differences over long periods due to over-cast cirrus with respect to the surface center could result in low level heating. Trapping of long wave radiation by a thick cirrus layer would produce relative warming in the column, although the magnitude of this effect is not known. Riehl (1963) pointed out that developing storms respond to influences from higher latitudes. Intensification could occur when a trough in the mid-latitude westerlies passes the longitude of a potential typhoon. Similarly, a developing tropical depression in the region of the cold TUTT may experience a direct circulation with ascent and therefore warming and intensification near the storm center with descent in the cold low.

The absence of deep convection in the case of POLLY may have been due to the extension over the Pacific of the warm Himalayan and Asiatic ridge. Equivalent potential temperature ($\bar{\theta}_e$) profiles for stations in the vicinity of the center of POLLY (Fig.10) were computed and are depicted by Fig. 11. Surface temperatures of 26C-27C may not have been warm enough to form deep convection as

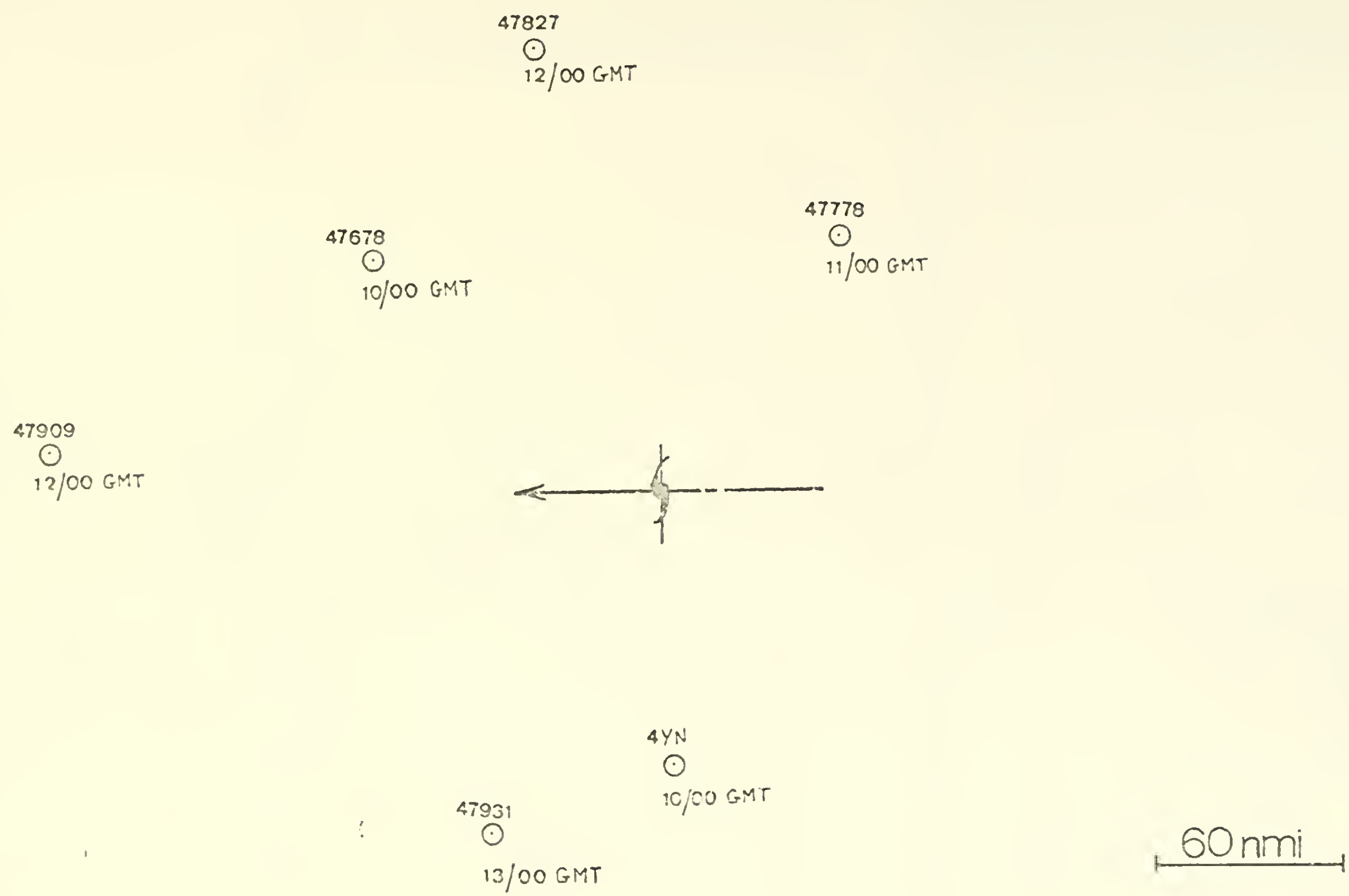

Fig. 10. The location of stations relative to the center of tropical storm POLLY for which profiles of equivalent potential temperatures were computed and are displayed in Fig. 11.

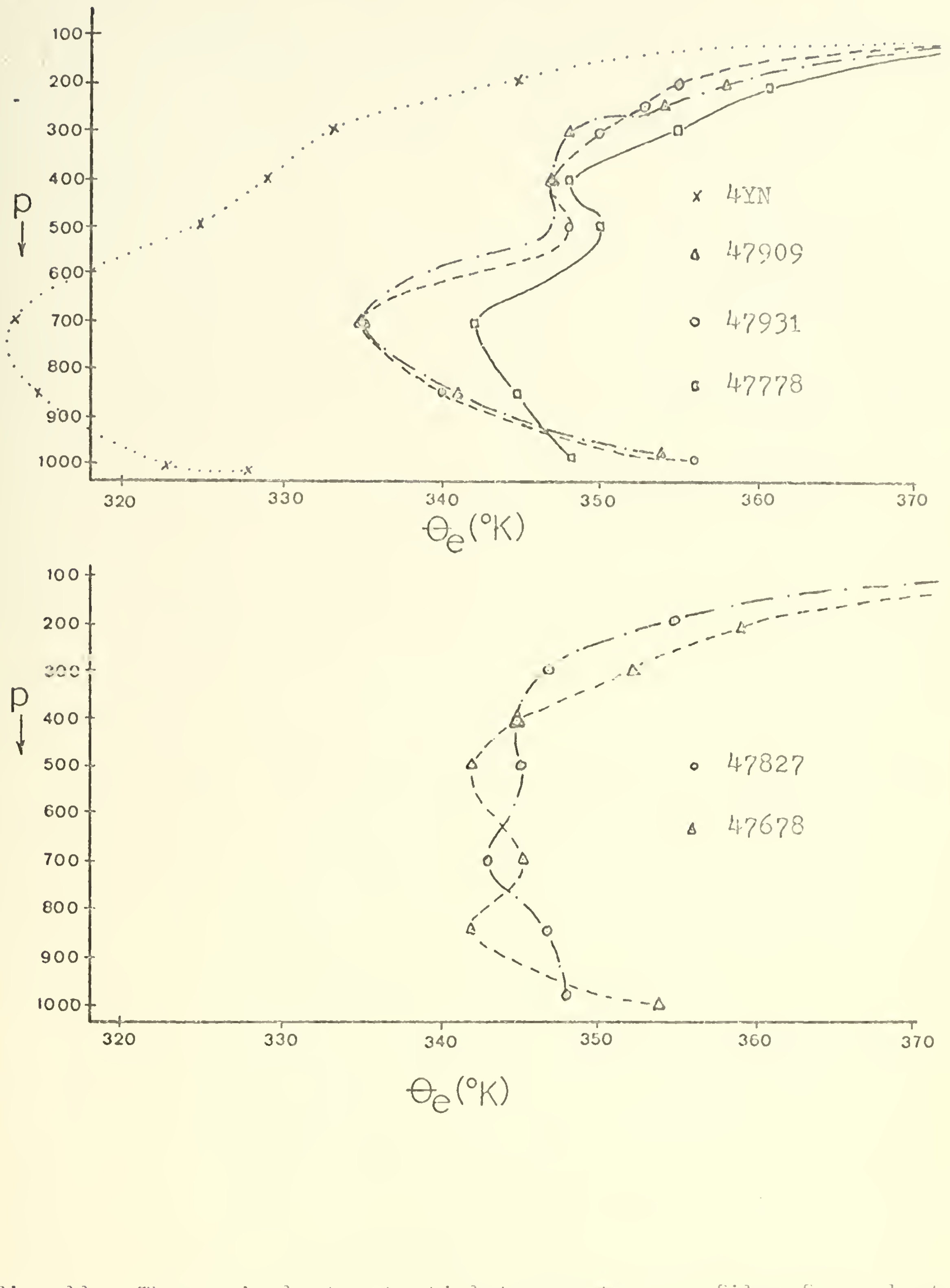

Fig. 11. The equivalent potential temperature profiles for selected soundings in the proximity of tropical storm POLLY.

a result of the warm air mass aloft. The θ_e profiles (Fig.11) tend to substantiate this. It should be pointed out that the only inversion was observed at Station 47909 between 847 and 805 mb with temperatures of 16.2C and 18.2C respectively.

C. NEPHANALYSIS

A striking feature of the cloud formations associated with POLLY was the lack of convective activity. The clouds, even those close to the center of the system, tended to be layered. The low clouds, cumulus and stratocumulus, were generally 2000-3000 feet in thickness. Some aircraft reports indicated a thickness of only 500 feet. The middle clouds, mostly altocumulus and altostratus, were remarkably well regimented into layers of about 2000 feet thickness with a few of 1000 feet and 3000 feet. The cirriform clouds were reported to be either 5000 feet in thickness or very thin.

The absence of cumulonimbus type clouds was conspicuous. One report at about 160 n mi south of the center indicated Cb with base at 1500 feet, top at 30,000 feet. All other Cb reports were beyond the 300 n mi radius, almost directly ahead of the direction of movement and were associated with islands.

The amount of cloudiness increased rapidly as one approached the center of POLLY. Aircraft reports of eye penetrations often indicated that the center was filled with clouds, generally stratocumulus. Table 4 lists the reports that indicated clouds in or over the center. Eye penetration reports substantiated the lack of convective activity associated with POLLY. Only one report, that of 1430 GMT 13 August indicated thunderstorm activity within 50 n mi of the center. The lack of convective activity was

TABLE 4

Penetration times and types of clouds found within the eye/center of POLLY.

DTG (GMT)	Type of Penetration	Cloud Type(s)	Amount	Tops (FT)	Eye Wall
10/0915	Low Level	Stratocumulus	10/10	NA*	No
10/2120	500 mb	Stratocumulus	10/10	NA	Poorly defined
11/0300	700 mb	Stratocumulus	10/10	NA	Closed
11/1558	700 mb	Stratocumulus	10/10	NA	Open**
		Altocumulus	6/10	NA	
11/2115	700 mb	Stratocumulus	NA	6000	Open
12/0300	700 mb	Broken Strato-cumulus	NA	NA	Closed
12/0955	Low Level	Stratocumulus	10/10	5000	Open
12/1415	Low Level	Penetration Aborted for	SAR		Open
13/0000	700 mb	Altostratus	10/10	NA	Open
		Stratocumulus	NA	NA	
13/0225	700 mb	Eye filling with Cu & Sc	NA	NA	Closed
		Altostratus	10/10	NA	
13/1050	Low Level	Stratocumulus	10/10	4000	Open
13/1430	700 mb	Thunderstorm Activity within 50 miles of the center			Open
14/0925	Low Level	Stratocumulus	10/10	3500	Open
14/1500	700 mb	Stratocumulus	10/10	4000	Closed
15/0250	700 mb	Stratocumulus	10/10	8000	Open
		Altostratus	10/10	NA	
15/0900	Low Level	Stratocumulus	10/10	3000 near center 7000 near edge	Open

* NA - Not Available

** Open means that the eye is formed by clouds representative of circulation but clouds are not present in all quadrants. It may also imply that the center of the storm is defined by feeder bands spiraling towards the center.

in accordance with the observations of Fett (1968) about shallow typhoons. Fett suggested that subsidence over the eye accounted for the absence of clouds as well as possibly providing the mechanics for heating the core of a shallow typhoon. However, on the basis of clouds, POLLY is somewhat different. The striking difference is that POLLY did have cloudiness in and over the eye. The stratocumulus tops tended to be around 4000-5000 feet. Thus in the case of POLLY there did not seem to be strong subsidence within the eye.

Analysis of prepared charts of the low, middle, and high clouds led to some general observations. The amount of cloud cover within a 300 n mi radius area tended to be greater in the right quadrants than in the left. Furthermore, it was noted that within 120 n mi of the center the tops of cumulus clouds tended to be higher in the rear quadrants and the bases generally lower in the left rear quadrant.

On the basis of middle cloud analysis it could be seen that the clouds were layered with thicknesses from 1000 to 2000 feet. The bases of altocumulus and altostratus were all above 8000 feet with the average at about 12,000 to 14,000 feet with a few reports as high as 19,000 feet. The amount of middle cloud cover increased rapidly towards the center of POLLY, especially within the 120 n mi radius. The cirriform cloud cover increased rapidly to overcast conditions within 100 n mi of the center. Where cloud layer thicknesses were reported, the thickness was either zero (i.e. very thin cirrus) or 5000 feet with the bases usually at 35,000 feet.

A more detailed description of the cloud analysis is found in Appendix A.

D. MAXIMUM WINDS DETERMINED FROM SATELLITE PHOTOGRAPHS

Table 5 is a tabulation of the maximum winds expected from nephanalyses of satellite photographs versus the actually reported maximum winds by reconnaissance aircraft. The significant factor in the case of POLLY was that in every case the satellite photograph interpretation considerably underestimated the maximum observed winds. In the later stages of the period the reported maximum surface winds were consistently 65 knots or higher. However, the Annual Typhoon Report (1968) reported POLLY as having maximum sustained surface winds of 55 knots, and hence the system was classified as a tropical storm.

E. STREAMLINES AND ISOTACHS

The composite analysis of relative streamlines and isotachs for the 1000, 700, 500 and 200 mb level are depicted in Figs. 12, 13, 14 and 15 respectively. During the analysis an effort was made to avoid forcing the streamlines to agree with the classical model. However, the available data suggested that POLLY had inflow at the 1000, 700 and 500 mb levels. At 200 mb there was definite cyclonic outflow from the center of POLLY, becoming anticyclonic about 90 n mi away from the center. This type of circulation was compatible with more mature typhoons (Riehl, 1954). For a shallow typhoon, however, this outflow was rather unexpected. As mentioned previously, Fett (1968) described typhoon BILLIE with straight northeasterly flow at 200 mb.

TABLE 5

Maximum winds in knots obtained by satellite photography interpretation and from aircraft eye penetration reports for tropical storm POLLY, August 10-15, 1968

Satellite Photo Interp. Date/Time (GMT)	Class	Wind (knot)	Date/Time (GMT)	Low Level Wind (knot) FL*	Low Level Wind (knot) SFC	700 mb Wind (knot) FL	700 mb Wind (knot) SFC
10/0532	Stage C	40	10/0240			68	55
			10/0915	NA**	90		
			11/0300			68	50
			11/2115			50	50
12/0233	Stage C	40	12/0300			65	60
			12/0955	NA	50		
			12/1415	NA	45		
13/0438	Category 1	35	13/0000			45	50
			13/0225			45	85
			13/1050	NA	50		
			13/1430	NA	45		
			13/2100			60	NA
14/0810	Only a partial photo of POLLY. Appears to be Stage C, 40 knot		14/0300			65	65
			14/0925	NA	70		
			14/2120			75	65
15/0917	Category 1	42	15/0250			43	65
			15/0900	NA	75		

* FL = Flight Level
** NA = Not Available

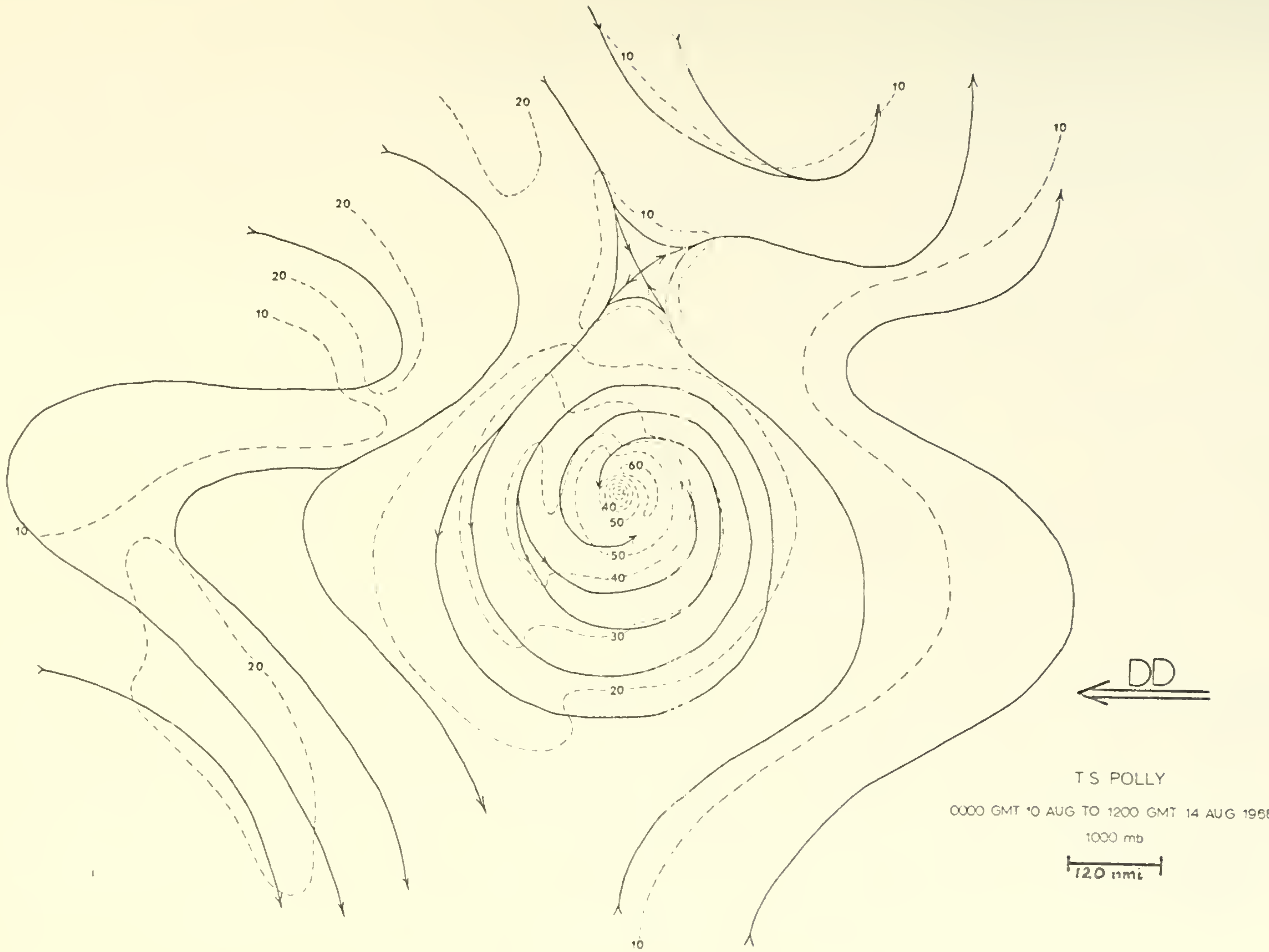

Fig. 12. The 1000 mb relative streamline and isotach fields for tropical storm POLLY. Arrow indicates direction of movement.

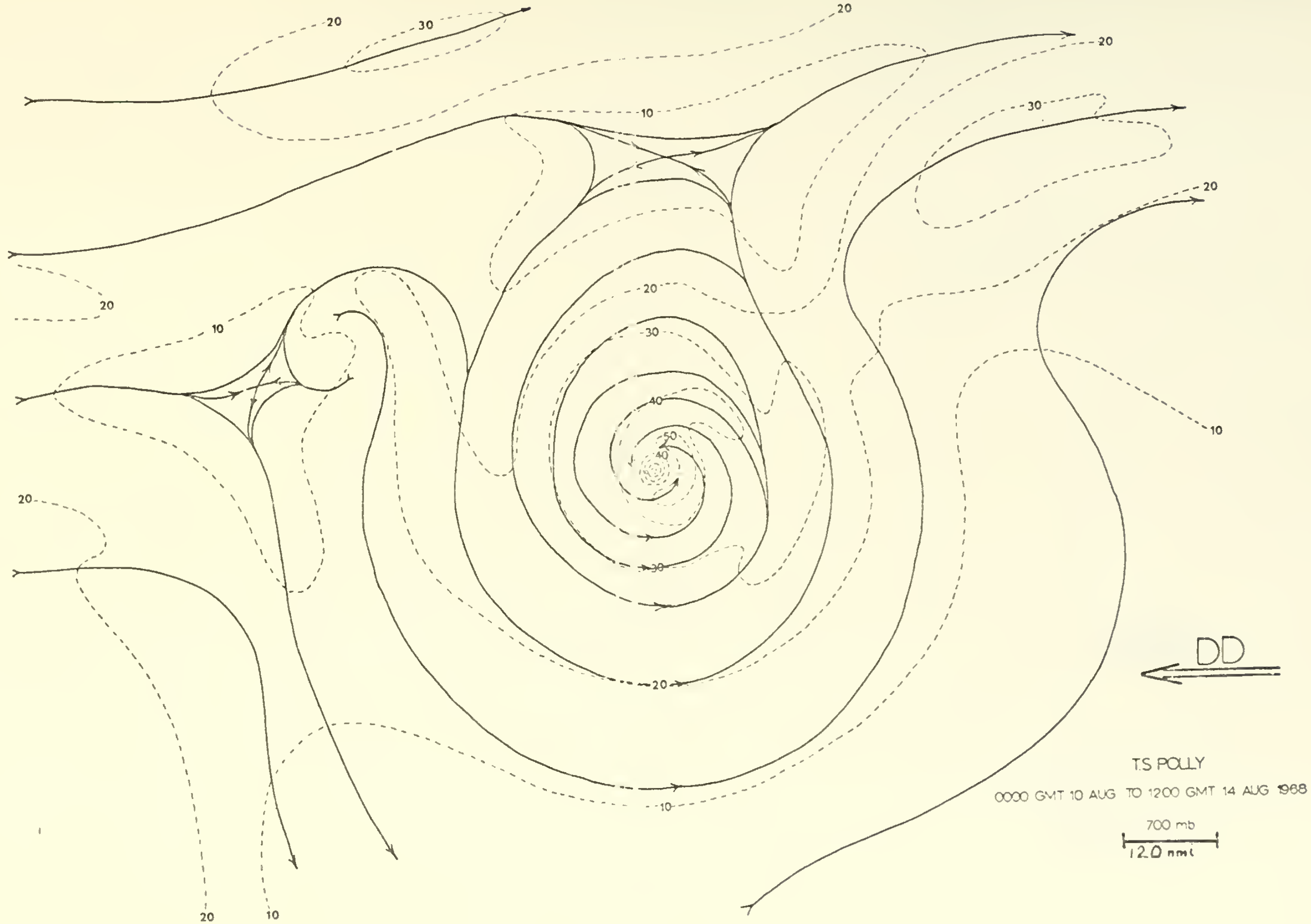

Fig. 13. The 700 mb relative streamline and isotach fields for tropical storm POLLY. Arrow indicates the direction of movement.

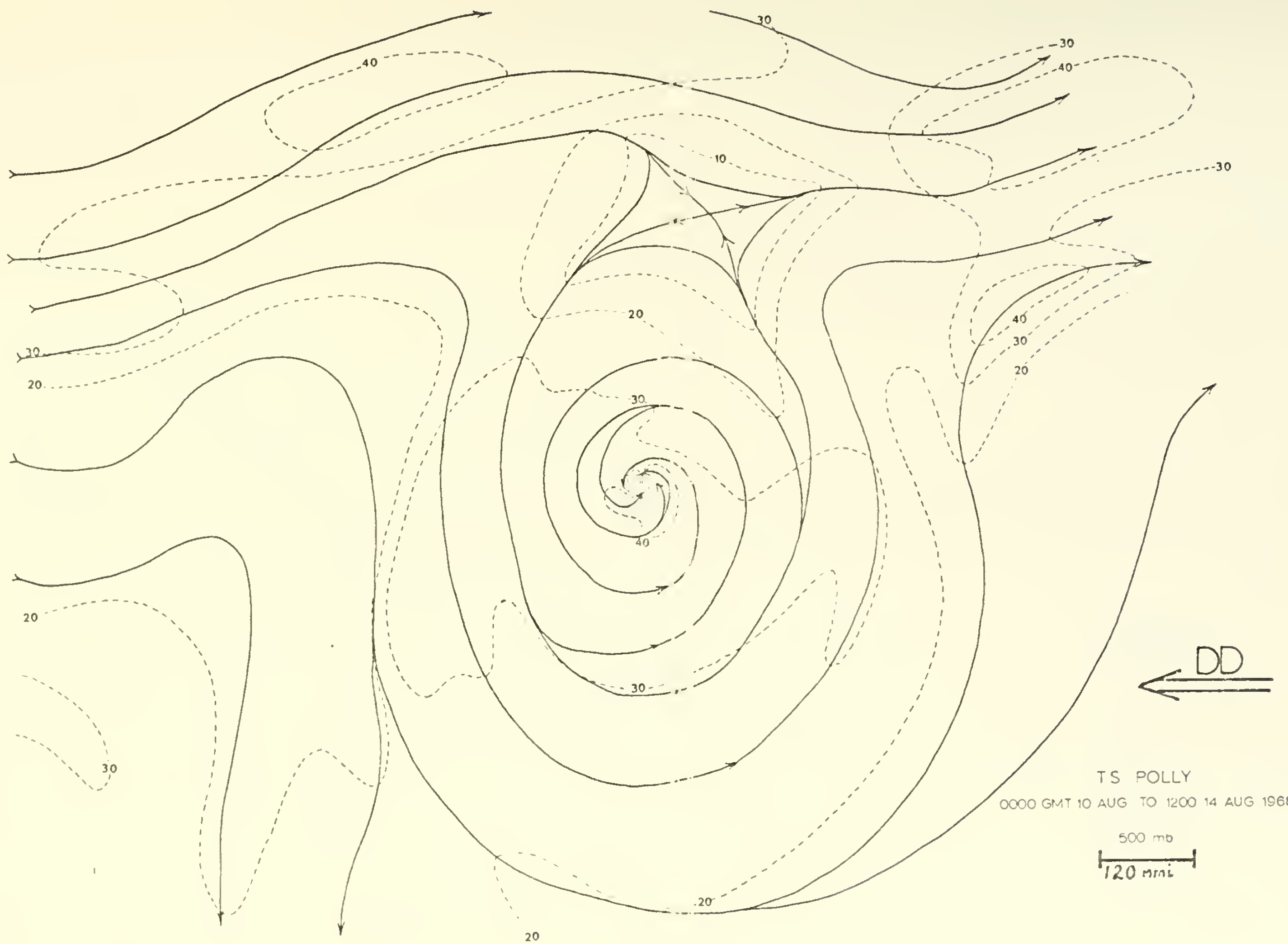

Fig. 14. The 500 mb relative streamline and isotach fields for tropical storm POLLY. Arrow indicates the direction of movement.

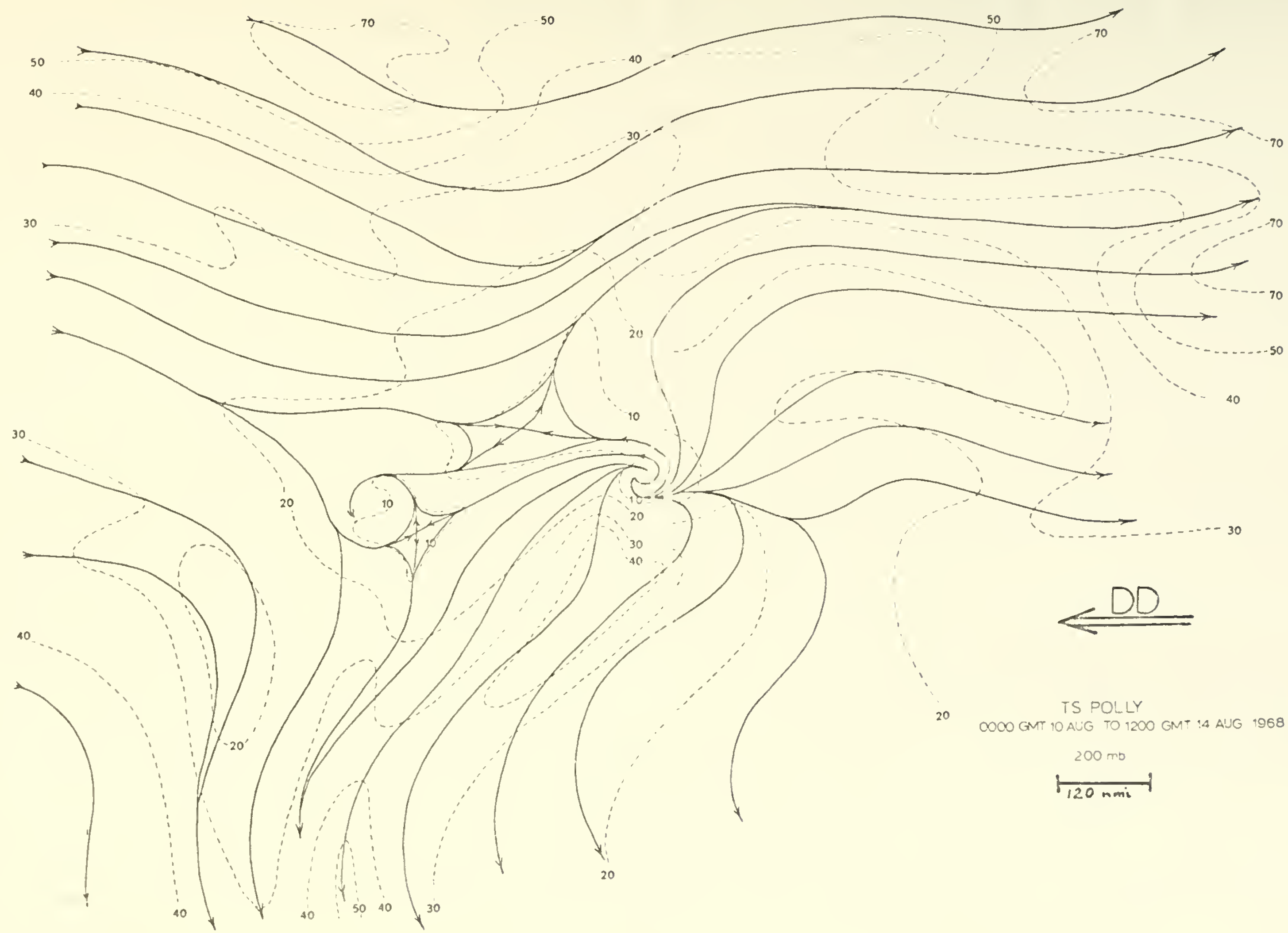

Fig. 15. The 200 mb relative streamline and isotach fields for tropical storm POLLY. Arrow indicates the direction of movement.

The wind speed decrease with height was as generally expected in a typhoon, as shown by Pike (1962), Gray (1968) and Riehl (1954). To check the consistency of the wind field and temperature analysis, the actual wind shears and the geostrophic and gradient wind shears based on the temperature analysis were computed. Actual tengential wind shears are presented in Fig. 16. These shears were averaged at 30 n mi intervals along cross sections parallel and normal to the movement of POLLY. Gray (1968) indicated that for tropical storm development and intensification the vertical wind shear between 850 mb and 200 mb should be ±10 knots or less. Large vertical wind shears prohibit the concentration of latent heat resulting from convective activity. As can be seen in Fig. 16, the shears below 500 mb were of the order of 10 knots beyond 90 n mi from the center. Shears in the upper regions, however, were of the order of 40 knots. It is suggested that these large shears at upper levels are a contributing cause of the lack of heating found aloft and the lack of convective activity.

Fig. 17 and 18 represent the comparison between actual, geostrophic and gradient vertical wind shears averaged at 30 n mi intervals for the 700 mb and 500 mb level respectively. Differences between the gradient and actual shears at 700 mb (Fig.17) implied the temperature gradient was reasonable near the center but was exaggerated further out. The temperature gradient at 500 mb was too large within 120 n mi, based upon the comparison between gradient and actual shears (Fig.18). The large difference between geostrophic and gradient wind shears displayed in Figs. 17 and 18 suggests the importance of the curvature term near the center of the shallow typhoon.

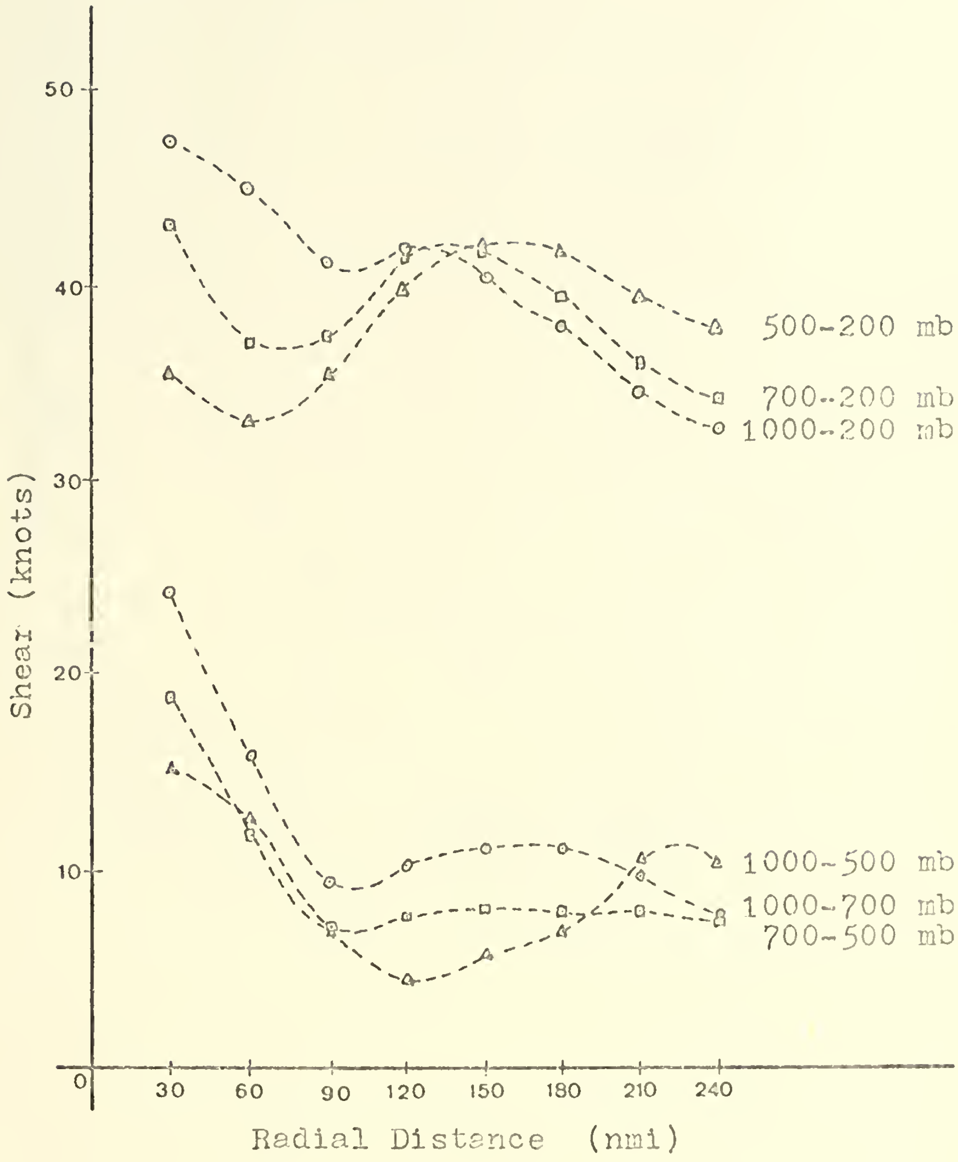

Fig. 16. The actual tangential vertical shears in knots averaged at 30 n mi intervals along cross sections parallel and normal to the movement of tropical storm POLLY, August 10-14.

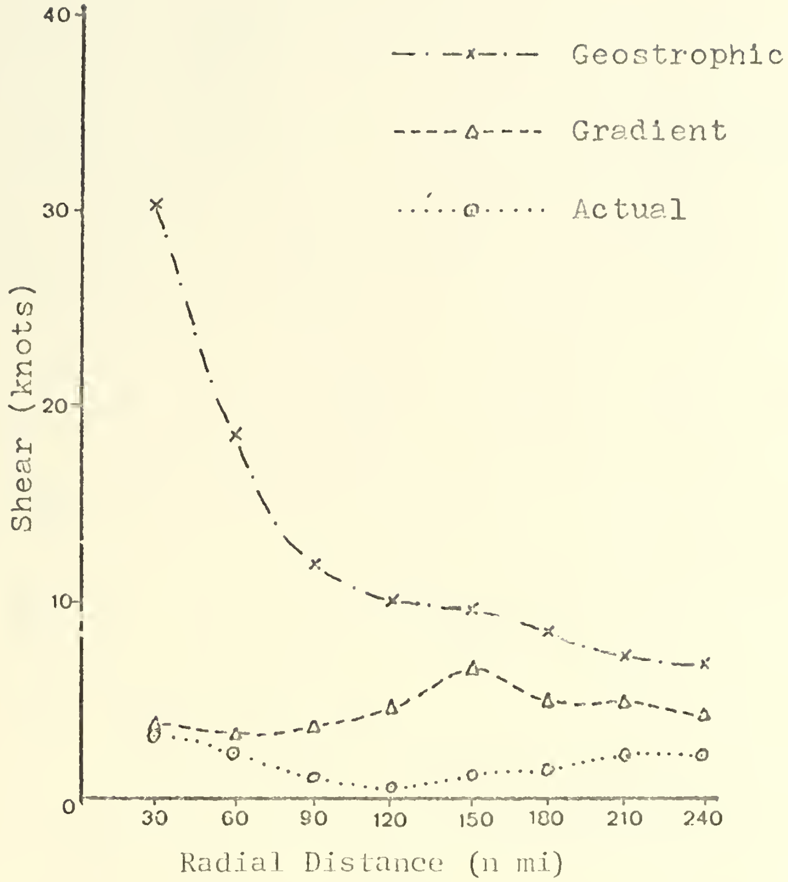

Fig. 17. Comparison of the absolute values of tangential actual, geostrophic and gradient vertical wind shears averaged at 30 n mi intervals along cross sections parallel and normal to the movement of tropical storm POLLY at 700 mb in units of knots/100 mb.

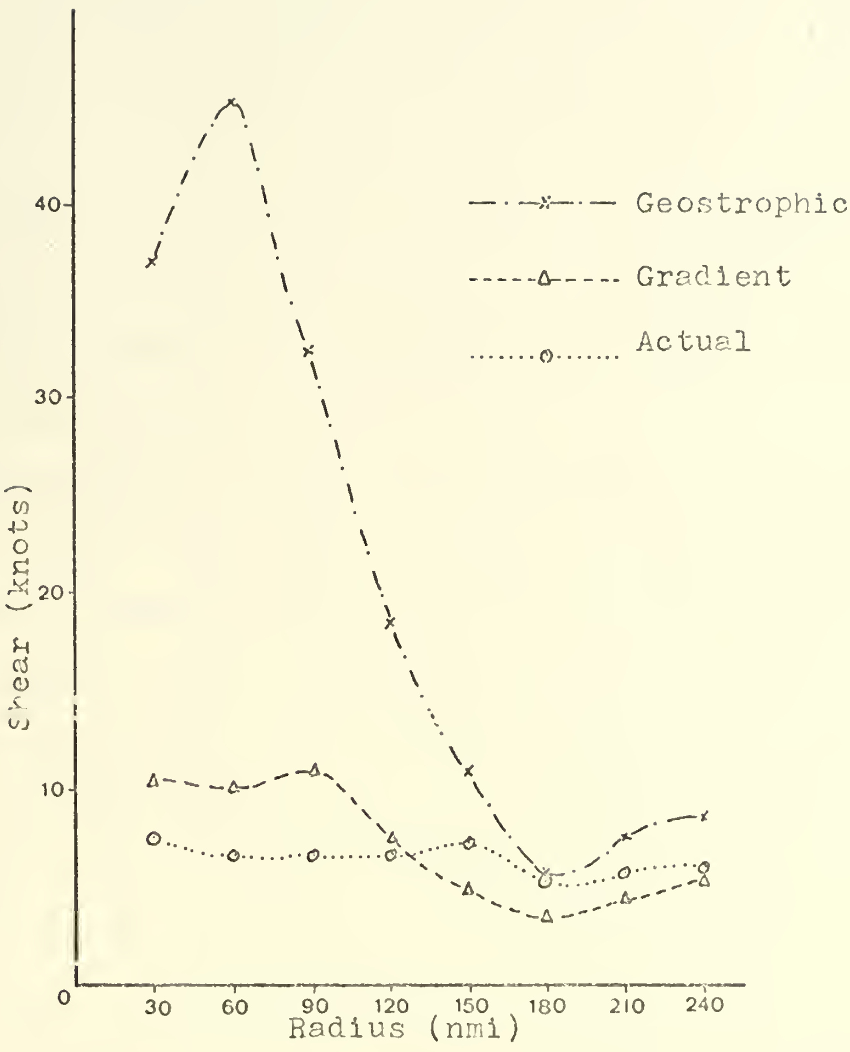

Fig. 18. Comparison of the absolute values of tangential actual, geostrophic and gradient vertical wind shears averaged at 30 n mi intervals along cross sections parallel and normal to the movement of tropical storm POLLY at 500 mb in units of knots/100 mb.

F. RELATIVE VORTICITY AND DIVERGENCE

The relative vorticities at 1000, 700, 500 and 200 mb levels are depicted in Fig. 19. Values were computed from the streamline and isotach analyses and then averaged at 30 n mi intervals from the center. The lower-level vorticity fields were of the order expected in a typhoon. Only a slight decrease of vorticity occurred between 1000 and 700 mb. Because the 200 mb level had cyclonic outflow, the relative vorticity field was positive to a radius of about 80 n mi and then became negative as the streamlines became anticyclonic.

The divergence profile at the four analysis levels shown by Fig. 20 was averaged similarly to the vorticity diagrams. Divergence fields for POLLY were similar to the typhoon model (Riehl, 1954) with significant convergence within 60 n mi of the center at low levels, and strong divergence near the center at upper levels. Fig. 21 represents the sum of the divergences for each level and the average velocity normal to the boundary of a 300 n mi by 330 n mi area centered around tropical storm POLLY. It can be seen that the level of non-divergence was slightly above 500 mb with convergence below and divergence above. The divergence at 200 mb appears to be excessive.

If the 200 mb analysis was in fact representative of the upper level structure of POLLY, there are some conflicting features associated with the storm. On the basis of wind shear computations much concentration of heat can not be expected aloft. The great amount of divergence aloft implies deep convection and release of latent heat. However, the nephanalysis showed that one of the primary characteristics of POLLY was a lack of deep convective activity.

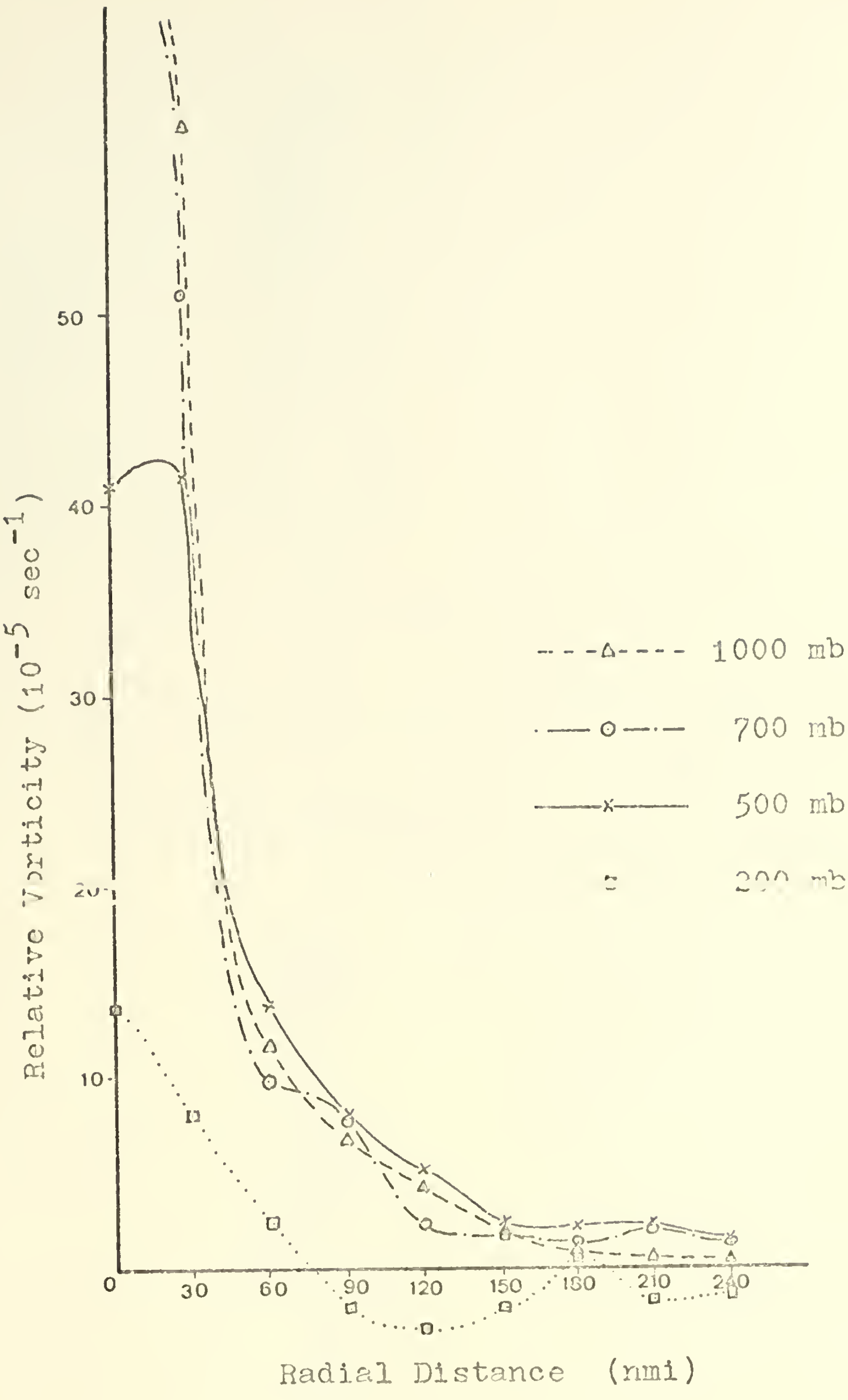

Fig. 19. The 1000, 700, 500 and 200 mb relative vorticity in units of 10^{-5}sec^{-1} averaged at 30 n mi intervals along cross sections parallel and normal to the direction of movement of tropical storm POLLY, August 10-14.

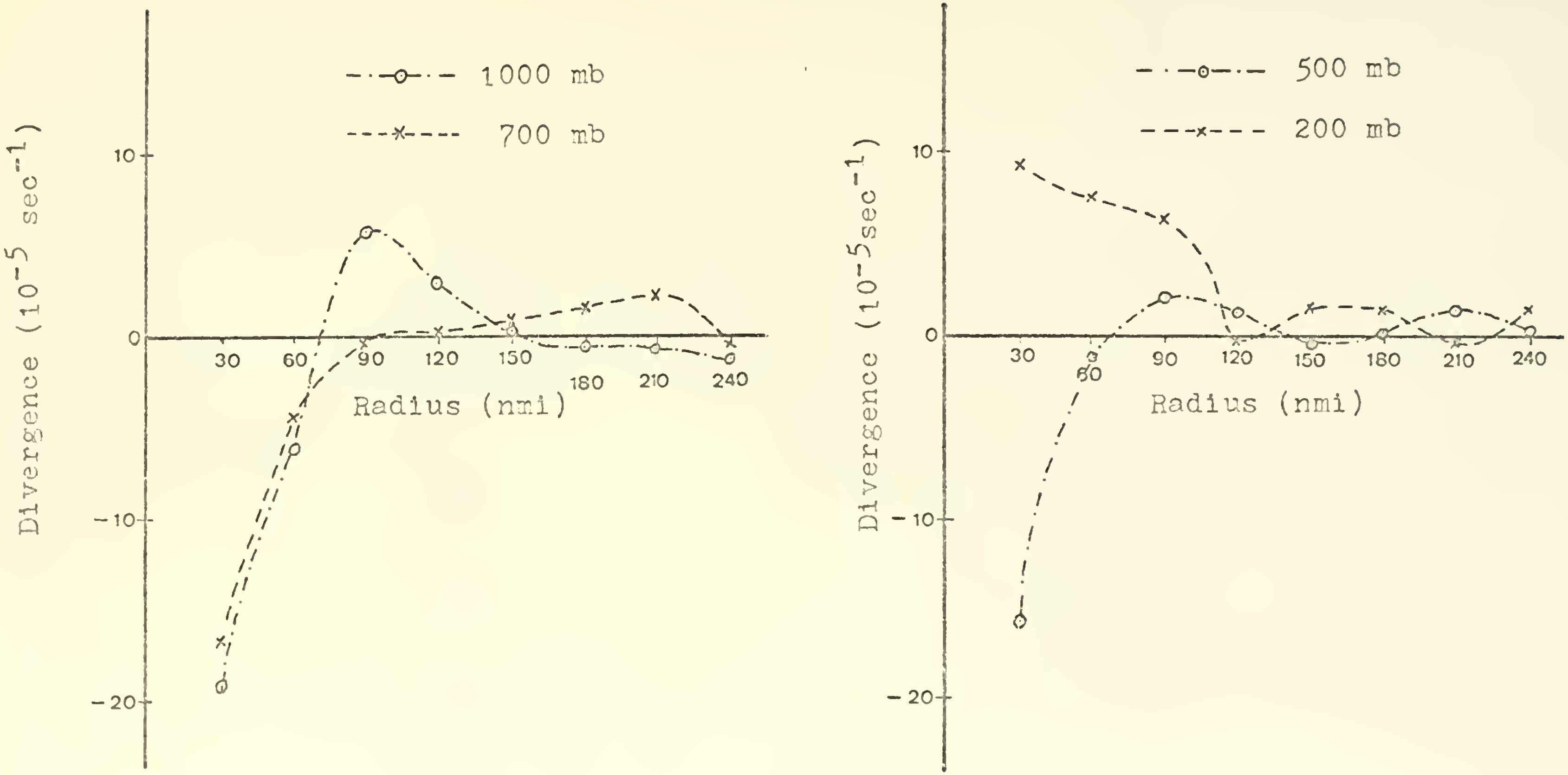

Fig. 20. The 1000, 700, 500, and 200 mb divergence fields in units of 10^{-5}sec^{-1} averaged at 30 n mi intervals along cross sections parallel and normal to the direction of movement of tropical storm POLLY, August 10-14.

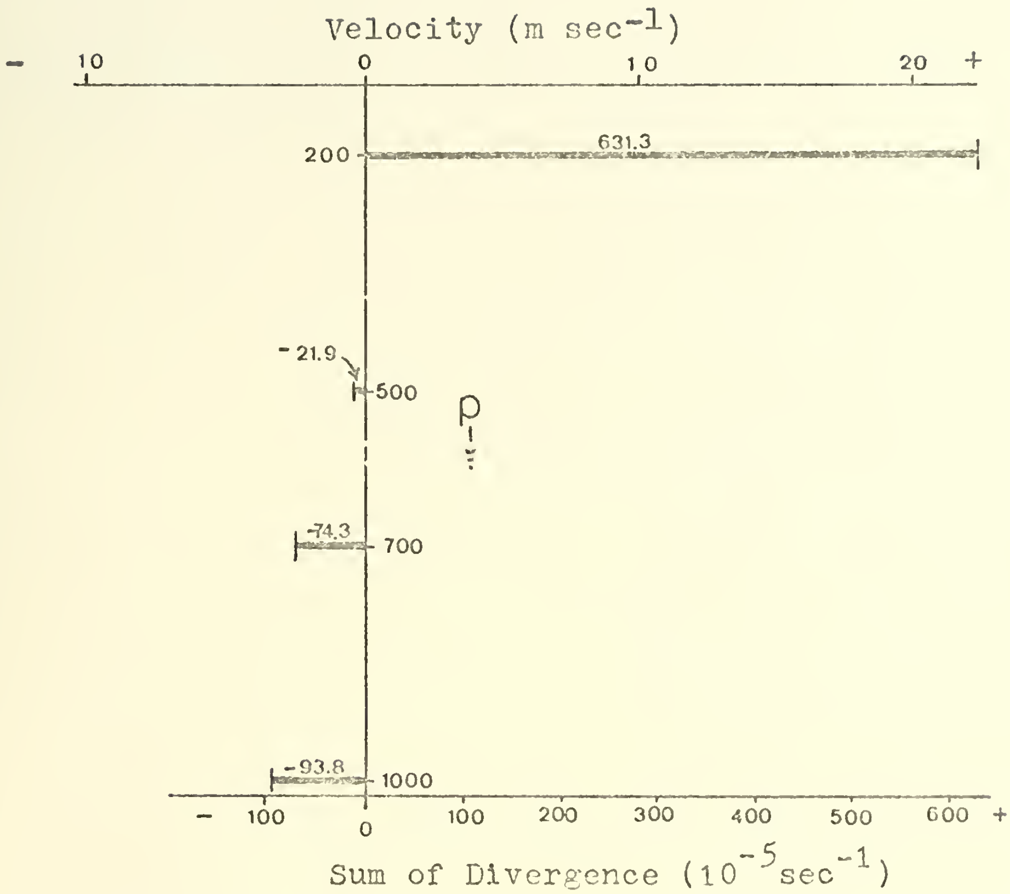

Fig. 21. Sum of divergence and the average velocity normal to the boundary of a 300 n mi by 330 n mi area centered around tropical storm POLLY.

Fett (1968) suggested that in typhoon BILLIE the warming of the eye resulted from subsidence of mid-tropospheric air into the region of the eye. From continuity considerations there would have to be compensating low-level divergence. Since there was cyclonic inflow and convergence associated with BILLIE near the surface, assumption of subsidence from aloft would require a region of strong divergence at an intermediate layer. Based upon the available data and the analysis, this type of convergence/divergence pattern did not exist with POLLY.

V. TYPHOON BILLIE

Although most of the effort in this research was on POLLY due to better data coverage, considerable time was spent on analysis of BILLIE. One of the objectives was to use RECCO reports to make a comparison between POLLY and BILLIE, since the latter storm was well documented by Fett (1968).

Basically, the two systems were similar in nature. The largest amount of warming occurred in the lower troposphere in typhoon BILLIE as was the case with POLLY. Satellite photography analysis (Fett, 1968) underestimated the actually observed maximum winds. This was also the case in POLLY. Based on nephanalysis, BILLIE was characterized by lack of convective activity and the clouds were stratified similarly to POLLY. An examination of Table 4 and Table 8 indicates that the eye structure of the two systems was basically the same, namely open eye wall with feeder bands spiraling towards the center. Clouds within the eye were generally topped off between 4000 to 5000 feet.

The two significant differences between POLLY and BILLIE were the high clouds above the eye and the upper level flow. Nephanalysis and verbal description in the RECCO reports of POLLY indicated definite overcast high cloudiness above the eye while BILLIE lacked high clouds. Overcast cirriform cover was found in the left quadrants of BILLIE, away from the center. Upper level flow at 200 mb associated with POLLY was cyclonic outflow becoming anticyclonic. Fett (1968) indicated that straight northeasterly flow was found

aloft with BILLIE. The analysis of available data substantiated this flow. However, the absence of upper air data in the immediate region of BILLIE would have also permitted a region of cyclonic outflow to be drawn.

Another difference between POLLY and BILLIE was that POLLY deviated considerably from the mean track and intensified at a latitude higher than normal.

A. EYE TEMPERATURES

Table 6 lists the low level eye penetration temperature reports for typhoon BILLIE obtained from RECCO reports for the period July 3-7. All reports, except the 0200 GMT 4 July report, indicated definite warming as the aircraft approached the center. The reports indicated an average increase of 1.7C inside the eye (1.5C increase for POLLY). Table 7 lists the upper eye penetration reports. These penetrations were near the 700 mb level and observed an average increase in temperature of 4.1C within the eye. POLLY had an increase of 4.2C.

At 500 mb and 200 mb there were no RECCO reports available. The 200 mb temperature analysis did not show a definite temperature eye. On the basis of the rawinsonde reports available the temperature field increased in temperature about 4C over a radius of about 240 n mi from the surface vortex. As with POLLY, the warming of the system appeared to be confined to the lower troposphere.

TABLE 6

Low-level eye penetration temperature reports for typhoon BILLIE, July 3-6, 1967.

Date/Time (GMT)	Max T in eye (°C)	Flight Level (mb)	Temp. outside eye (°C)	Flight Level (mb)	Temp. Increase (°C)
03/0940	25.0	NA*	23.1	NA	1.9
03/1530	24.9	968	23.9	970	1.0
03/2124	24.5	1960 ft	24.0	1730 ft	0.5
04/0200	24.5	1840 ft	25.0	1750 ft	-0.5
04/1030	25.6	951	24.6	955	1.0
05/1600	26.1	949	23.1	952	3.0
05/2140	26.7	959	24.0	951	2.7
06/1836	30.5	941	26.8	950	3.7

* NA = Not Available

TABLE 7

Upper-level eye penetration temperature reports for typhoon BILLIE, July 4-6, 1967.

Date/Time (GMT)	Max T in eye (C)	Flight Level (mb)	Temp. outside eye (°C)	Flight Level (mb)	Temp. Increase (°C)
04/1625	9.4	680	6.0	680	3.4
04/2120	17.2	726	14.1	726	3.1
05/0330	18.5	3220 m	13.5	3220 m	5.0
05/0931	18.0	700	11.0	700	7.0
06/0354	17.5	700	11.5	700	6.0
06/0720	17.5	700	14.5	700	3.0
06/0946	19.0	700	15.5	700	1.5

The remainder of eye penetration reports for July 6-7 give the maximum inside temperatures at about 950 mb and the outside eye temperatures at about 700 mb.

B. NEPHANALYSIS

The summary of the clouds for typhoon BILLIE is based upon station and aircraft reports between 0000 GMT 3 July and 1200 GMT 7 July 1967. As in the case of POLLY, the cloud patterns associated with typhoon BILLIE indicated a definite lack of convective activity. There was only one report of cumulonimbus activity within 300 n mi of the center. Low clouds were generally 2000 to 3000 feet in thickness. There were a few reports which indicated thicknesses greater than 3000 feet, a case not as frequent with POLLY. On the average the tops of cumulus and stratocumulus tended to be higher with increasing distance from the center while the bases remained at about the same altitude.

The middle clouds were well regimented in layers 1000 to 2000 feet thick. The bases and tops of the altocumulus and altostratus were somewhat lower within 120 n mi of the center. Altostratus was predominant in the left quadrants, especially in the left rear between 90 to 240 n mi. The right front quadrant was conspicuous with the absence of middle cloud reports even though low and high clouds were indicated. This feature was not found in POLLY. The rear quadrants generally had more middle level cloud cover. Bases ranged from about 6000 feet to 15,000 feet with a very few indicating 20,000 feet. All middle clouds associated with POLLY had bases above 8000 feet.

The cirriform clouds were either very thin or at most 5000 feet in thickness throughout the field. There were no reports of overcast cirrus or cirrostratus in the right quadrants or over the eye of BILLIE. Fett (1968) suggested that the lack of high cloud cover over the eye of BILLIE was the result of the northeasterly

flow above the system. The left quadrants had reports of overcast cirriform clouds. One report only 30 n mi from the center in the left front quadrant indicated overcast cirrus. A more detailed description of the clouds associated with typhoon BILLIE is found in Appendix B.

Table 8 lists those eye penetration reports which remarked about the presence or the lack of clouds within or over the eye of BILLIE. The type, amount and tops of the clouds were entered when available.

TABLE 8

Penetration times and types of clouds found within or over the eye/center of typhoon BILLIE, July 4-7, 1967.

DTG (GMT)	Type of Penetration	Cloud Type(s)	Amount	Tops (ft)	Eye Wall
04/1700	700 mb	Altostratus	10/10	13000	None
04/2120	700 mb	No Clouds	-----	-----	Open*
05/1600	Low Level	NA**	-----	-----	Open
05/2140	Low Level	No Clouds	-----	-----	Open
06/0354	700 mb	Stratocumulus	NA	NA	Open
06/0720	700 mb	Stratocumulus	NA	5000	Open
06/0946	700 mb	Cumulus	NA	NA	Open
07/0430	700 mb	Type not Indicated.	NA	5000	Open
07/0920	700 mb	Type not Indicated	10/10	4000-5000	Open

* Open means that the eye was formed by clouds representative of circulation but clouds were not present in all quadrants. It may also imply that the center of the typhoon was defined by feeder bands spiraling towards the center.

VI. TROPICAL STORM LORNA

Tropical storm LORNA was not investigated in detail. Naphanalysis based on RECCO and land station reports for the period 0000 GMT 25 November to 2400 GMT 28 November 1969 is included in Appendix C. LORNA was characterized by lack of convective activity similar to typhoon BILLIE and tropical storm POLLY. There was only one report of cumulonimbus activity 180 n mi ahead of LORNA in the right front quadrant. This report was associated with thunderstorm activity over land.

Low level clouds of cumulus and stratocumulus had bases generally between 1500 to 2500 feet with tops from 2000 to 6000 feet. In comparison with POLLY and BILLIE, cumulus clouds associated with LORNA had greater thicknesses. Within 60 n mi the layers were about 2000 feet, but further out the thicknesses increased to 3000-4000 feet.

Altocumulus and altostratus were generally 2000 to 3000 feet thick with the bases highly variable anywhere from 6000 to 18,000 feet. One report about 12 n mi from the center in the left rear quadrant indicated overcast altostratus. All other reports of overcast middle type clouds were in right quadrants 55 n mi or further away from center.

Available cloud reports indicated that cirriform cloud cover increased with distance away from the center. Nimbus III infrared photographs of LORNA further substantiated this. Cirrostratus clouds were predominant with LORNA while cirrus was predominant

with POLLY and BILLIE. Bases of the high clouds, when indicated, were generally between 25,000 feet and 28,000 feet, with a few reports at 30,000 feet. The thicknesses were generally 2000 feet, considerably less than the 5000 feet for POLLY and BILLIE.

VII. THE COMPOSITE MODEL

In this section a composite model which was developed from the analysis of the tropical cyclones discussed previously will be presented. The model also includes the results of the low level analyses of NADINE and OLIVE. Analyses of these two systems substantiated the characteristics found in the previous sections.

On the basis of available data, the shallow typhoon is a warm core, cyclonically rotating wind system. The system lacks an eyewall in the classic sense. Clouds representative of cyclonic circulation, or feeder bands spiraling towards the center, usually define the eye. A closed eye is not a characteristic. The eye of the storm, however, is definitely warm core. Most of the core warming tends to be in the lower troposphere below 500 mb. Upon reaching typhoon intensity, the winds are most intense near the surface, reaching speeds between 70 and 80 knots.

Nephanalysis of satellite photographs generally underestimates the maximum expected winds. Using the nephanalysis procedure as outlined by Project FAMOS (1967), Stage C or C+ is found with expected winds of 25 to 30 knots.

Clouds associated with the shallow typhoon indicate a lack of convective activity. The clouds are regimented into layers with cumulus or stratocumulus 2000 to 3000 feet thick, and altocumulus or altostratus usually 2000 feet thick. Cirriform clouds are found to be either very thin or a few thousand feet in thickness with maximum tops at 35,000 feet. Within the eye the clouds are

topped off around 4000 to 5000 feet although occasionally tops are 7000 to 8000 feet. There is often an absence of clouds within the eye or above the eye at high altitudes.

With the available data it was not possible to clearly define the upper level flow to be expected with a shallow typhoon. Fett (1968), based on available data, indicated strong northeasterly flow at the 200 mb level over typhoon BILLIE. Sadler (1967) in discussing typhoon KATHY, which lacked the vertical extent of a normal typhoon, depicted straight flow above KATHY. The data at 200 mb in POLLY's case indicated cyclonic outflow over the surface vortex and then becoming anticyclonic.

The vertical wind shears in the lower troposphere are low enough to enable warming of the system and allow for intensification to typhoon force. However, the shears in the upper troposphere are of the order of 30 knots or more and may prevent the system from intensifying into a full scale typhoon.

VIII. SUMMARY AND CONCLUSIONS

Available data from five tropical cyclones verify the existence of shallow type typhoons which do not fit into the framework outlined for the classical model. The model presented in the previous section is by no means complete, and further research into the structure and mechanics of formation and maintenance is needed. Ability to recognize this type of a typhoon is particularly important if airborne reconnaissance is not available. Reliance on satellite observations alone for prediction of these storms could prove disastrous.

To enable better definition of upper level structure of the model, reconnaissance flights at 500 mb and in the 250 mb to 200 mb region are imperative. Without this data accurate description of the system will not be possible.

APPENDIX A

Nephanalysis of tropical storm POLLY
10-14 August 1968

Distance from center (n mi)	Quadrant	Remarks
00-60	Right Front	Cumulus with bases 1500' to 2000' with tops 5000'. One report at 11/1500Z indicated overcast Cu 15 n mi from the center with base at 1500' tops 3000'. Stratocumulus with 9/10 cover, base 2000' tops 5000' at 60 n mi ahead of center. All reports but one indicated altocumulus with bases at 8000', 4/10 cover. Only one report of high clouds in the 60 n mi circle showed 10/10 cirrostratus with base at 30,000'.
00-60	Right Rear	Cumulus, 4/10 cover, bases at 2000', tops 10,000' maximum. Altostratus with overcast indicated by three out of four reports. One report indicated As with base at 7000', tops at 8000'.
00-60	Left Front	Cumulus and stratocumulus with tops 4000-5000'. Altostratus and altocumulus, overcast, with bases 12,000-17,000'.
00-60	Left Rear	Cumulus and Stratocumulus with tops 4000-5000'. Only one report of altostratus, 10/10 cover, no bases or tops indicated.
60-120	Right Front	One aircraft and one station report available in the front quadrants showed cumulus type clouds, overcast, with bases down to 1500'. Tops not indicated. No report of middle clouds available. Only one report indicated cirrus, 3/10 cover.

Distanee from center (n mi)	Quadrant	Remarks
60-120	Right Rear	Cumulus type elouds with bases 1200 to 1500 ' with tops up to 9000'. Cover from 7/10 to overcast. Stratoeumulus present with bases 2000-4000', tops generally 5000-6000' with a maximum of 9000' reported. One aircraft report showed nimbostratus. Only two of fifteen reports indicated complete eloud cover.
60-120	Right Rear	Altostratus and altoeumulus with 1/10 to 10/10 cover. Altostratus base 12,000 to 13,000 feet, tops 14,000 to 15,000 feet. Altoeumulus 7000 to 10,000 feet base, tops 9000 to 12,000 feet. Cirrus and eirrostratus 1/10 to overeast, bases 30,000 feet, tops at 35,000 feet.
60-120	Left Front	For low type elouds see comments in the right front region. Altocumulus with base at 10,000 feet, tops 14,000 feet, 7/10 to 8/10 cover. Only one report in the front quadrants indicated cirrus, 3/10 cover.
60-120	Left Rear	Cumulus with bases 1300 to 1500 feet, tops around 5000 feet with one report up to 10,000 feet. Stratocumulus with bases 2000 to 4000 feet, tops 4000 to 5000 feet. Altoeumulus and altostratus from 5/10 to overcast. Bases from 8000 feet up to 17,000 feet with tops at 9000 feet to 19,000 feet. The eloud thicknesses generally 2000 feet. Wide variation of base and eloud top heights. Cirrus and cirrostratus 5/10 to 10/10 eover, bases at 30,000 feet, tops at 35,000 feet or else very thin.
120-240	All	Beyond the 120 n mi radius no report indicated overcast high eloud type cover. Cirroform clouds are present with bases around 30,000 to 35,000 feet with very thin or 5000 foot thickness indicated.

Distance from center (n mi)	Quadrant	Remarks
120-240	Right Front	Stratocumulus bases generally reported at 2000 feet with tops around 5000 feet. Cumulus cloud bases from as low as 1500 feet to 2000 feet with tops around 5000 feet but a few reports indicated as high as 20,000 feet. Altostratus and altocumulus 5/10 to 9/10 cover, bases 8000 to 10,000 feet, tops 10,000 to 12,000 feet.
120-240	Right Rear	The tops of cumulus type clouds tended to be lower than in the front quadrants, being generally 3000 to 5000 feet with bases 1500 to 2000 feet. Stratocumulus bases 2000 to 3000 feet with tops around 6000 feet but extending to 9000 feet. Altostratus and altocumulus with bases generally 8000 to 10,000 feet, tops 10,000 to 12,000 feet. Cover from 1/10 to overcast.
120-240	Left Front	For Low type clouds see under right front description. Altocumulus and altostratus 6/10 to overcast, bases 8000 to 12,000 feet with tops 10,000 to 12,000 feet. One report indicated overcast altostratus with base at 28,000 feet.
120-240	Left Rear	Cumulus and stratocumulus similar in character as found in the right rear quadrant. At the forward edge of the quadrant at about 160 n mi from the center is the only cumulonimbus report within a 240 n mi radius. Out to 240 n mi the right quadrants tend to have more cloud cover than the left quadrants. This observation may however be due to the availability of more reports in the right quadrants. Altocumulus and altostratus, 4/10 to 8/10 cover, bases 10,000 to 12,000 feet with tops 13,000 to 14,000 feet. Some reports indicate base at 17,000 feet, tops at 19,000. Two reports, south and southwest of center at about 210 n mi have nimbostratus in conjunction with altocumulus.

APPENDIX A (cont.)

Distance from center (n mi)	Quadrant	Remarks
240 -	All	There was some cumulonimbus activity ahead of the center of POLLY at a distance of over 300 n mi. Reports of middle clouds became sparse with only a few aircraft reports to indicate thickness of altocumulus and altostratus. Thickness, as before, generally 1000 to 2000 feet. The general trend was for less cloud cover the further away the report was from center.

APPENDIX B

Nephanalysis of typhoon BILLIE
3-7 July 1967

Distance from center (n mi)	Quadrant	Remarks
00-60	Right Front	One report of cumulus, 9/10 cover, base 1500 feet, top 4000 feet. No report of middle clouds except for eye penetration report of 04/1700Z which indicated overcast over the eye. Thin cirrus, 1/10 cover, base at 35,000 feet.
00-60	Right Rear	Cumulus 3/10 to 8/10 cover, bases 1000 to 2000 feet, tops 4000 to 5000 feet. One report indicated Cu top at 7000 feet. Altocumulus 9/10 cover, base 7000 feet, top 8000 feet. Cirrus 5/10 to 8/10 cover. Bases and tops not indicated on reports.
00-60	Left Front	Cumulus 7/10 to overcast, bases 1000 to 2000 feet, tops 9000 to 10,000 feet. One report of overcast Stratocumulus 60 n mi from center, base 1000 feet, top 5000 feet. Altocumulus 1/10 cover, base 12,000 feet, top 15,000 feet. One report 30 n mi from center reported cirrus, base or top not given.
00-60	Left Rear	Cumulus 5/10 to overcast, bases as low as 600 feet but generally 1000 to 2000 feet, tops 3000 to 4000 feet. Only one report of stratocumulus, base 2000 feet, top 3000 feet. Altostratus, 9/10 cover, base 12,000 feet, top not indicated. One report of thin cirrus, 5/10 cover, base 30,000 feet.

Distance from center (n mi)	Quadrant	Remarks
60-120	Right Front	Only one report of seven indicated cumulus, 2/10 cover, base not given, top at 10000 feet. The rest strato-cumulus 4/10 to overcast, bases generally 1000 feet, tops 3000 to 4000 feet but up to 5000 feet. No middle clouds indicated. Thin cirrus 1/10 to 5/10 cover at 30,000 feet. Cirrostratus 8/10 cover, base 30,000 feet, top 35000 feet.
60-120	Right Rear	Cumulus 5/10 to overcast, bases 2000 feet, tops 3000 to 4000 feet but one report up to 12,000 feet about 70 n mi from center. One altostratus report, overcast, base 12,000 feet, top not indicated. Very thin cirrus 1/10 to 5/10 cover, base 30,000 feet.
60-120	Left Front	Cumulus and stratocumulus, mostly overcast, bases generally 2000 feet, tops 3000 to 5000 feet. One report indicated cumulonimbus activity, base 1500 feet, top not given. One report of altostratus in two layers with 6/10 cover. One layer with base at 7000 feet, top 8000 feet. Second layer base 15,000 feet, no top included. Very thin cirrus, 4/10 cover, at 30,000 feet.
60-120	Left Rear	Cumulus, 3/10 to overcast, bases 600 to 1500 feet, tops 1500 to 2500 feet. One report indicated Cu with top at 8000 feet. No stratocumulus type clouds. Altocumulus, 8/10 cover, base 10000 feet, tops 11,000 to 12,000 feet. Altostratus, base 15,000 feet, top 16,000 feet. One report of cirrostratus, overcast, base 30,000 feet, top 35,000 feet.

Distance from center (n mi)	Quadrant	Remarks
120-240	Right Front	Mostly cumulus with 1/10 to 9/10 cover, bases generally 1000 to 2000 feet, tops 4000 feet with two reports indicating 10,000 feet. Stratocumulus with bases 1000 to 2000 feet, tops 4000 to 5000 feet. One report of altocumulus 6/10 cover, base 12,000 feet, top 13,000 feet. Cirrus, 1/10 to 5/10 cover, base at 30,000 feet, tops 30,000 or 35,000 feet.
120-240	Right Rear	Cumulus and stratocumulus, 3/10 to 8/10 cover with bases generally 2000 feet, tops 4000 to 5000 feet but up to 8000 in a few cases. One report indicated thin stratus, base 1200 feet, top 2000 feet. Altocumulus and some altostratus, 3/10 to 9/10 cover, bases generally 15,000 feet, tops 16,000 to 17,000 feet. Thickness of layers very thin or about 2000 feet. Thin cirrus, 5/10 to 8/10 cover, base at 30,000 feet.
120-240	Left Front	Mostly cumulus type clouds, 3/10 to 9/10 cover, bases around 1500 feet, tops ranged from 4000 to 10000 feet. Stratocumulus, base 1000 feet, tops 4000 feet. Altocumulus 5/10 to 6/10 cover, thicknesses 3000 feet with bases 11,000 to 12,000 feet. Altostratus 5/10 to overcast, bases 6000 feet to 9000 feet, thickness about 1000 feet. Cirrus, 5/10 to overcast, base 30,000 feet, tops 35,000 feet.
120-240	Left Rear	One low cloud report available indicated 3/10 cumulus, base 1000 feet, top 2000 feet. Altostratus only, overcast, base 15,000 feet, tops not indicated. - Cirrus, 8/10 to overcast, bases and tops not reported.

Distance from center (n mi)	Quadrant	Remarks
240 +	Right Front and Rear	Cumulus, 3/10 to 8/10 cover, bases at 2000 feet, tops ranged from 3500 to 10,000 feet with average about 5000 feet. No stratocumulus indicated. Very few reports of middle clouds. Those available indicated altocumulus with bases from 10,000 to 20,000 feet, tops 12,000 to 22,000 feet. Thicknesses generally about 2000 feet. Reports of high clouds were sparse beyond 240 n mi in all quadrants. Those available indicated cirrus, 1/10 to 4/10 cover, bases and tops not reported.
240 +	Left Front and Rear	Cumulus 3/10 to 6/10 cover, bases generally 1000 to 2000 feet, tops 4000 to 5000 feet but up to 8000 feet on a few reports. One report about 360 n mi ahead of center indicated Cb activity, no base or top indicated. Reports of middle clouds were very few. Available ones indicated altostratus and altocumulus, 5/10 to overcast, bases fro 12,000 to 15,000 feet, thicknesses about 2000 feet. For cirriform clouds see above under the right quadrants.

APPENDIX C

Nephanalysis of tropical storm LORNA
25-26 November 1969

Distance from center (n mi)	Quadrant(s)	Remarks
00-60	All	Cumulus with 2/10 to 6/10 cover, bases 1500 to 2000 feet, tops 3000 to 4000 feet. One report of strato-cumulus with base 1000 feet, top 1300 feet. Altostratus and altocumulus with bases from 7000 to 17,000 feet, thick-ness 2000-3000 feet. One report of overcast As 12 n mi from center in left rear quadrant. Only three reports of cirrostratus, 5/10 to 9/10 cover, base 28,000 feet, tops 30,000 feet.
60-120	Right	Cumulus generally 5/10 or more cover, bases 1500 feet, tops 6000 feet. Stratocumulus base 1500 feet, top 1800 feet. Altostratus 2/10 to overcast, bases 7000 to 10,000 feet. Cirrostratus 3/10 to overcast, bases 24,000 to 25,000 feet, tops not indicated.
60-120	Left	Cumulus 2/10 to 6/10 cover with bases 1500 feet, tops 6000 feet. Stratocumulus up to 5/10 cover with bases 1500 feet, tops 3000 to 4000 feet. Altocumulus 2/10 to 5/10 cover, bases 6000 to 7000 feet. Cirrostratus, mostly overcast, bases and tops not indicated.
120-180	Right	Cumulus and stratocumulus 1/10 to 6/10 cover. Cu bases generally 1500 feet, tops 4000 to 6000 feet. Sc bases highly variable, tops 3000 to 6000 feet, with 1500 to 3000 foot thicknesses.

APPENDIX C (cont.)

Distance from center (n mi)	Quadrant(s)	Remarks
120-180	Right	Altostratus 2/10 to overcast, bases highly variable from 7000 to 16,000 feet, thickness 1000 to 2000 feet. Altocumulus bases 7000 feet, tops 8000 to 10,000 feet. Cirrostratus 2/10 to overcast, bases 28,000 feet, tops 30,000 feet. Few reports of cirrus, 5/10 cover, base 35,000 feet, top not indicated.
120-180	Left	Cumulus and stratocumulus 2/10 to 6/10 cover, bases 1500 to 2000 feet, tops 6000 to 7000 feet. Altocumulus and altostratus bases 6000-7000 feet, thickness 3000 feet. Overcast cirrostratus, thickness not reported.
180-300	All	Reports sparse, expecially in left quadrants. Cumulus and stratocumulus with bases 1500 to 5000 feet, tops 3000 to 6000 feet. No altostratus or altocumulus reports in left quadrants. Reports in right quadrants indicate As and Ac with 1/10 to overcast, bases highly variable, thickness 1000 to 2000 feet. No high clouds reported in left quadrants. Four reports of cirrus and cirrostratus, 3/10 to 9/10 cover, base 28,000 feet or 35,000 feet. Tops not reported.

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13. ABSTRACT

During the past few years the existence of tropical cyclones of typhoon intensity, but lacking the vertical extent of the "classical" model, have been reported. Five such "shallow" systems were investigated by compositing reconnaissance and rawinsonde data with respect to the center. Although emphasis was placed on POLLY (1968), a composite model was derived from the five storms. Some of the characteristics found in the model were the lack of convective activity, the existence of a warm core in the lower levels but very little warming aloft, and an open eyewall rather than the closed eye found in classical typhoons.

Some comparisons with the classical model are made but detailed reconnaissance data are needed to explain the differences between shallow and normal typhoons.

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